Formulation & Calibration of a Numerical model of the tidal hydraulics of McCormacks Bay

A report submitted in partial fulfilment of
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Under supervision of
Professor D.L.Wilkinson

by

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Abstract

The experimental investigation in this report was conducted both as indicator of the problems in McCormacks bay, and also as a base for the calibration of a numerical model of the hydraulic characteristics of the bay. There are some issues of public concern associated with the bay at the present time. These are related to dominant algae populations and their related problems, and the desire to preserve the existing bay as a healthy marine environment.

Numerical models can be a useful tool to test various management options. A component of this study involved the calibration of a numerical model which described the response of the bay to tidal functions in the estuary.

Calibration was achieved using data from measurements taken on the eighteenth of December 1996. The model was based specifically around the main central culvert running under the causeway.

The model showed that an increase in the depth of this culvert would increase the range of water levels in the bay by up to 23%. This is significant and would increase the tidal exchange in the bay, thereby promoting circulation.

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Notation

u_C = the critical velocity

z_E = level in the estuary

z_B = level in the bay

B_C = the critical width (breadth)

g = the gravitation constant (9.81m/s/s)

y_C = the critical depth

h_C = the height of the culvert

c_L = the loss coefficient

A_B = the area of the bay

Q = the flow rate m^3/s

A_0, A_1, A_2 = constants used in shape fitting equation

α, β = constants used in power relationship

1.0 Introduction

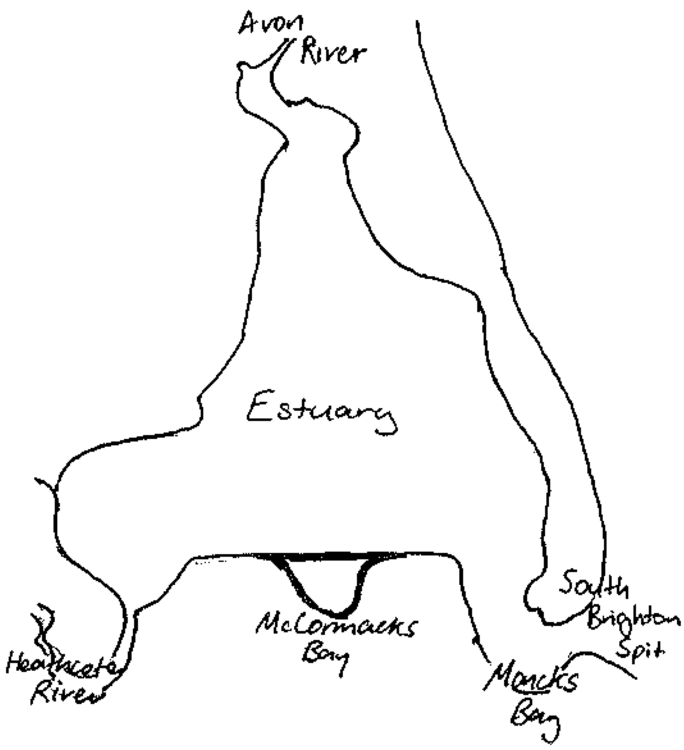
1.1 Background/History

The Canterbury plains dominate the landscape around the Banks Peninsula and the adjacent Christchurch city. The low, gently sloping area which the city now lies has two drainage channels, one snaking through the present city and exiting at the top of the estuary. The second forms at the base of the Port Hills suburb of Cashmere and progresses along the base of the hills to the bottom of the estuary as shown in figure 1. These two rivers flow towards the junction of Banks peninsula's volcanics, the gravels of the Canterbury plain and the ocean.

From a geological perspective, the estuary in its present form has only been in existence for a very short time, but it must be remembered that estuaries are shaped by dynamic forces such as floods, sedimentation and ocean storm events. So that changes can occur over time scales of days during extreme events.

Covering approximately 880 hectares and located 12 kilometres from the centre of Christchurch city, the Avon-Heathcote Estuary hosts an abundance of life. It also provides the urban inhabitants of the surrounding areas with a playground within easy reach.

Figure 1, Right
This figure shows the Christchurch estuary and its main features with McCormacks Bay located along the Southern edge.



McCormacks Bay was initially a part of the overall estuary which provided a sheltered well-sunned area for birds and other aquatic life. With the development of the Sumner farther along the coastline, transport routes were constructed. In 1907 a causeway was constructed across the entrance of McCormacks Bay for the purpose of establishing a tram route between Sumner and the city. This causeway formed an embayment with the estuary on one side and the bay on the other. After the removal of the tram network the causeway was widened to accommodate traffic and to then again to provide recreational areas. Tidal exchange between the estuary and the bay is facilitated by three culverts. The largest of these being 6m in width the other two being considerably smaller piped culverts.

There were no noticeable problems with the area until the mid to late 1960's when algae populations within the bay began exploding due to increased nutrient inputs. Since then the ecology has slowly settled on seasonal equilibrium with high production of algae and sea cabbage during the summer. This results in an aesthetic problem excess of algae as well as the odour problem caused by algae carried above the high tide mark decaying in the sun. The exact cause of the increased algae populations in the bay and the estuary as a whole is unknown but increased nutrient inputs from the Bromley sewage treatment plant (since causeway construction) are suspected.

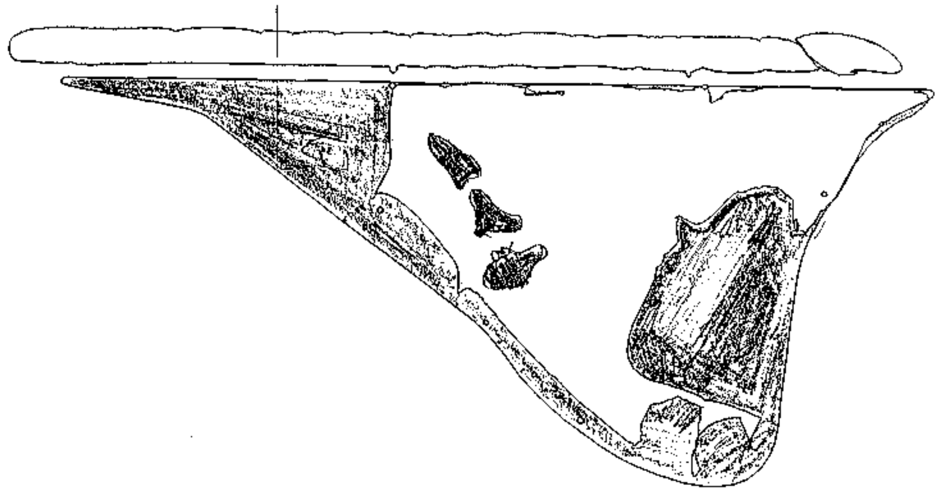
1.2 Geography/Hydrology

Situated at the base of the Port Hills and bounded by hills to the east and west the bay is a natural drainage path. Storm run-off would in the natural state of the catchment have drained into brooks these combining to form a stream running along the base of the valley. Since the development of the surrounding hills and valley extensive stormwater facilities have been installed to relieve local flooding. Simple road drainage culverts and domestic services, combined with the construction of a man made stream to intercept stormwater from the hills provide a comprehensive stormwater network. The construction of the artificial stream at the base of the valley with rip-rap base and an integral silt trap have eased the likelihood of sedimentation during normal storm activity. This became an issue when the development was taking place as sedimentation was a predicted result of storm behaviour for the catchment. It was thought that active sedimentation was playing a large role in the factors leading to the current odour problem. This problem would have been compounded by the erosion of loess from the Port Hills. Investigations have been undertaken by the CCC (Christchurch City Council) into completely infilling McCormacks Bay. This almost eventuated, in the mid-1960's but in the end it was not carried out. It has been clearly pointed out that the local inhabitants and interest groups strongly oppose any further reclaimation. Apart from the reclamation of the western corner and the south eastern corner little else has progressed. Islands were constructed, in the north-western part of the bay to provide sanctuary for birds see Figure 2. As it was thought that the islands might help relieve the odour problem by reducing the area of the tidal mudflat in the bay.

1.3 Connection with the estuary

McCormacks is connected to the estuary by the three culverts running under the causeway. The largest of these is a six metre wide box culvert with rip-rap rock type base with invert located 0.1m below mean sea level. This culvert is located just west of the rock spur separating the main bay and the eastern bay. The two other culverts are located at the western and eastern ends of the causeway. The western culvert is made up of two 450mm diameter pipes gently sloping into the bay. The eastern culvert is a 1.2m diameter concrete pipe which is gently sloping into the estuary.

Figure 2, below shows the bay as it exists at the present time with reclaimed areas shaded in. This diagram clearly shows the extent of reclamation.



1.4 Reasons for construction of the causeway

During the early part of this century, the Sumner area began to develop with large numbers of people travelling from Christchurch city during the weekend. The lack of adequate road capacity and with the construction of tram routes in the city itself, a tram route around the edge of the estuary to Sumner was established. The route could be made as straight as possible to increase efficiency as there was no need to stop often on the route. This necessitated the construction of several causeways across small bays along the way. The McCormacks bay causeway constructed in 1907 was in fact the largest of these, larger than its present size.

The causeway was constructed as a component of the tram route to Sumner. In 1939 the increase in motor vehicle use brought about a widening of the causeway to accommodate a single lane of motor traffic in addition to the tramway. This was then widened to two lanes and the use of the trams was finally stopped. The current causeway is the original widened for motor-vehicle traffic. The original causeway was constructed to reduce avoid construction of a more costly route around the then bays shoreline.

1.5 Features of the bay

The bay is sheltered on both sides by hills, the hill to the east especially providing significant shelter from the prevailing easterly wind. The bay also catches a large proportion of the available sunlight. For these reasons the bay tends to be warmer and quieter than the rest of the estuary. The bay is also sheltered to some degree by the causeway structure itself. The causeway has three culverts allowing limited tidal flushing and natural drainage routes for stormwater run-off. The causeway inhibits tidal exchange with the estuary and this has reduced the already low velocities within the bay. It would appear that originally the bay formed part of a circulation pattern for the Heathcote River's waters. When the causeway was constructed an island further out in the estuary and towards the mouth of the Heathcote which channelled water in around the bay was eroded away rapidly and this may have stopped the circulation of river water round the bay. This natural feature which once was, is no longer, possibly due to the construction of the causeway. The bay itself is a natural point of storm water inflow, with a small stream and drainage culverts running down the valley into the bay. Siltation due to sedimentation seems to be minimal at present however most of the fine sediments in the south of the bay appear to have come from the surrounding hillside catchments. Further developement of the catchment area may lead to renewed sedimentation.

1.6 The biology of the bay

Terrestrial vegetation around the bay is very similar to the estuary as a whole. It is primarily the marine vegetation within the bay which differs to that of the estuary. Dense beds of sea lettuce and red algae thrive in McCormacks Bay. These provide abundant food for grazing snails but also deny survival to most species beneath them. When the snails decompose, they take up available oxygen in the sediments which becomes oxygen starved, leading to anaerobic decomposition, this is one source of odour problem in the bay. Very few animals can live in this nitrogen rich anaerobic environment. It is for this reason that burrowing shellfish and air breathing snails such as the mudflat snail cannot inhabit the bay. In areas of the bay which are free of algae the selection of aquatic life is similar to that which can be found in the main estuary.

In McCormacks Bay itself, white faced heron, pied stilts and kingfishers are commonly seen. All three species nest around the bay. Until 1985, one or more reef herons visited the artificial rocky shoreline of McCormacks Bay each winter. Sadly, these birds have not been seen in recent years. Since 1990 royal spoonbills have extended their feeding range on the estuary to include McCormacks Bay and sometimes more than a dozen are present. With work planned through the 1990s to create bird roosting islands and replant saltmarsh in the bay, even more birds may return to this long troubled corner of the estuary. Such large numbers of birds both in the estuary and in McCormacks Bay have an effect on the water quality and nutrient levels. The large population of birds living on or near the Bromley oxidation ponds is known to contribute considerably to the amount of faecal coliforms present. At times of large bird numbers in the estuary the high nutrient (nitrogen and phosphorus) content of their excretions can make a significant contribution to the nutrient level of the waters of the estuary. [1]

Estuaries are important they provide a link between salt and fresh water species providing an ecological buffer zone. Estuaries are very fertile and contain large populations of marine plants and animals as well as providing for humans and birds. The Christchurch estuary is relatively young, having been formed within the last ten thousand years. During the last 150 years the rivers feeding the estuary have been heavily urbanised and the development of man-made oxidation ponds (associated with the Bromley sewage treatment plant) has changed the characteristics of the estuary. Though these changes have not brought about drastic changes to the estuary overall they have brought about changes in nutrient and toxin levels thereby limiting fishing and normal biological development.

Due to their sensitive nature estuaries can be used as indicators of the overall health of the environment. This can be directly seen in the case of water pollution but can also be applied to air quality and noise and dust problems.

As Christchurch developed into the city which it currently is (approximate population 287,000), rivers and estuaries were developed for civic services. Both the Avon and Heathcote Rivers were used as a disposal source for storm-water. The city introduced a treatment scheme for both industrial and domestic sewage, based at Bromley on the western edge of the estuary. The Bromley sewage treatment works presently discharge approximately 140,000 m^3 of secondary treated effluent into the estuary each day. Oxidation ponds were constructed to form the final stage of treatment for the effluent before disposal into the estuary. The sewage treatment process removes a considerable amount of the biological oxygen demand (BOD) but nutrients such as nitrogen and phosphorus remain only slightly reduced and exist in concentrations greater than normal. The effluent was originally released constantly during the tidal cycle, but presently the effluent is released on the outgoing tide and this sees most of it flushed from the estuary without causing too much of an imbalance. The high nutrient levels in the treated

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"The Estuary - Where Our Rivers Meet The Sea" Christchurch's Avon-Heathcote Estuary and Brooklands Lagoon, Edited by S-J Owen, Produced by the Parks Unit Christchurch City Council effluent have potential to cause problems with plant growth in the estuary as plant life normally limited by available nitrogen.

The estuary has historically been used for food collection by the Tangata Whenua and more recently by the growing urban population of the region. As well as fishing and food gathering primarily for human consumption, there has also been recreation use in terms of fishing and water based activities and outdoor recreation.

1.6.1 Controlling factors of algal growth

There are many controlling factors for algal growth these being:

- Availability of nutrients: algae require minimum levels of nutrients to survive and thrive. The levels of nutrients are the base line for algal growth, with nitrogen being the most essential.
- Exposure to sunlight: both algae mentioned need to be immersed to photosynthesise. Areas submerged would promote growth through lower stress and longer growth periods per tidal cycle.
- Temperature: both of the algae prefer the warmer water of sheltered areas though still higher temperatures also restrict the growth (hence lower concentrations in summer).
- Salinity of the water: the algae do require some salinity to grow and the ideal salinities for growth vary at salinities up to 80% of sea water.
- Wind: this plays an important part in not only generating currents and moving the algae but also in drying it out when exposed.
- Currents: these, generated by either wind or tidal exchange through the culverts play an important part in the growth of algae. This tends not to grow in the relatively fast channels around the culverts and the drainage channels from the mudflats.
- Grazing, the amount of grazing usually limits the maximum size of a population of algae. It would appear though, that the anaerobic silts tend to restrict the type of grazers and therefore the numbers of grazers.

From an examination of the distribution of the algae in the estuary in the years through 1968-1973 (figs. 6.15-6.24 Knox and Kilner 1973), it is obvious that the population of algae in the bay is the most persistent of all those in the estuary. Ever since a foothold was gained following a migration of algae through the bay in the mid to late 1940's, it has been the most significant population. The bay's climate and topography tend to suit the most ideal conditions for the algae.

The bay is in a state of balance at the moment, despite the dense and well entrenched algae, but problems remain due to the exclusion of marine life from the mud beneath the algae and the odours produced. The driving force behind the search for a solution to these problems are the concerns of local residents about the decline in the visual and olfactory aesthetics of the bay. Marine lifeforms are inherently flexible and the change in the ecosystem has not left permanent damage to any part of it. The areas of dense anaerobic muds in the bay are certainly unpleasant and if there was a way to easily rehabilitate the sediments this would be the best option.

1.7 Environmental Issues at McCormacks Bay

1.7.1 Siltation

At present, the amount of sediment eroding from surrounding hills and new subdivisions and depositing in the bay appears small. The development of the new subdivisions has required several new stormwater facilities to be put in place therefore considerably increasing the likelihood of siltation. The risk of loss of storage in the bay due to sedimentation is high. The high probability of sediment being trapped within the bay, would see the bay filling up with sediment, permanently increasing bed levels in the bay. The time-line for such activity has been lengthened by the use of preventative measures. The routing of storm flows through silt traps and artificial channels minimises soil loss in the lower areas of the subdivision, therefore slowing the problem down and trapping a considerable amount of silt and other matter before it can progress to the bay itself.

Silt, provides a trap for the nitrogen rich products of sea lettuce decay. Creating a layer of deoxygenated mud, this prevents normal biological activity ie animal and plant life within the deoxygenated (anaerobic) layers of mud. This reults in the production of methane and hydrogen sulphide.

1.7.2 Odours

Wave action transports algae to the high tide line where it accumulates and decomposes. The process of decomposing initially gives off methane and carbon dioxide. Later on when the organic remains are decomposing anaerobically in the sediments, they give off hydrogen sulphide gas and this represents a major odour nuisance. In summer time when the gas is given off and the easterly wind carries it to residential areas adjacent to the bay. Gas produced along Humphrey's drive also contributes to a significant odour problem in the area during summer.

1.8 Possible remedial works

There are several options for trying to control the problems of increased algal growth and development of the bay, but there are basically to solve the problems as they exist. These include reclaiming the bay, dredging the silt and widening existing or installing new culverts. The possible remedial options involve close consultation with the local inhabitants. Past surveys indicate that the community would like the bay to remain in as natural a state as possible (Combined Estuary Assoc. Letter to the Christchruch Drainage Board (CDB) Aug 1985, in the CCC copy of then CDB job sheet No.3056/2).

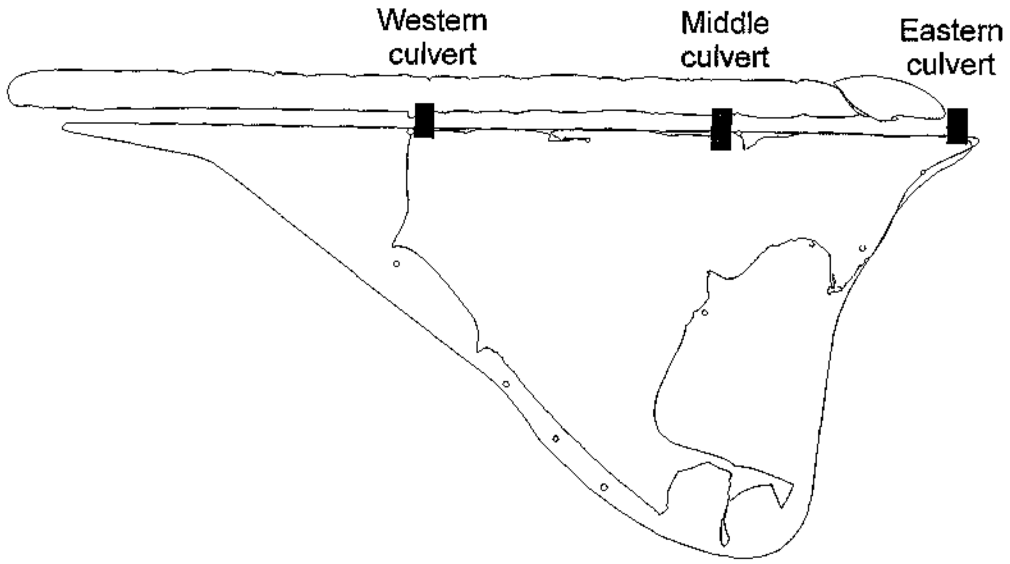
To return the bay to its original state, would take a considerable amount of time and effort. The benefits of such dramatic action may not be large. The marine environment is a very dynamic one, able to cope with changes in conditions. This what has happened in McCormacks bay the marine life have adjusted, first to the construction of the causeway and secondly to the algal growth problem. The algae problem seems to be confined to the southern edge of the estuary, and is primarily a nuisance due to the odours and aesthetics. Other options such as chemical treatment and dredging are not attractive either and would appear to be a temporary measure. The reason for the dominance of the algae in the Bay still has to be clearly understood. There are many differing opinions on what can be done to reduce the algal problem and improve the environment of the Bay. These have to carefully weighed up and action taken, so the ecosystem can be made acceptable to all those concerned.

2.0 Tidal Characteristics of the Estuary and Bay

The bay is linked with the estuary by three culverts, the larger of which is located in the middle of the causeway. The bay consists of the main central and western embayment with freshwater input at the southeastern corner behind the park. A smaller eastern bay above the park is seperated by a rock spur. The bay drains to 12% of its full volume on the low tide exposing wide flats of silt. This is not the case for the eastern bay which remains covered in water for a considerably longer time and forms larger drainage channels.

The invert levels of the culverts determine the lower range of tidal exchange in the bay. The tide in the estuary is close to sinusoidal but of a slightly smaller range at 1.74m, than the ocean tide at 1.9m, due to the restrictions imposed by the entrance channel to the estuary.

Figure 3 Below, showing a plan view of the bay as it is today including the bird islands and the areas which have been reclaimed in the last thirty years. The locations of culverts are marked on the figure, western, main and eastern culverts.



2.1 Measurements

The tidal levels were monitored both in the estuary and the bay during a complete tidal cycle. In conjunction with this monitoring velocity measurements were taken in the main culvert during the full tidal cycle. The aim of the exercise was to calibrate a numerical model, which described the tidal behaviour in McCormacks bay, so that it could be used for planning purposes.

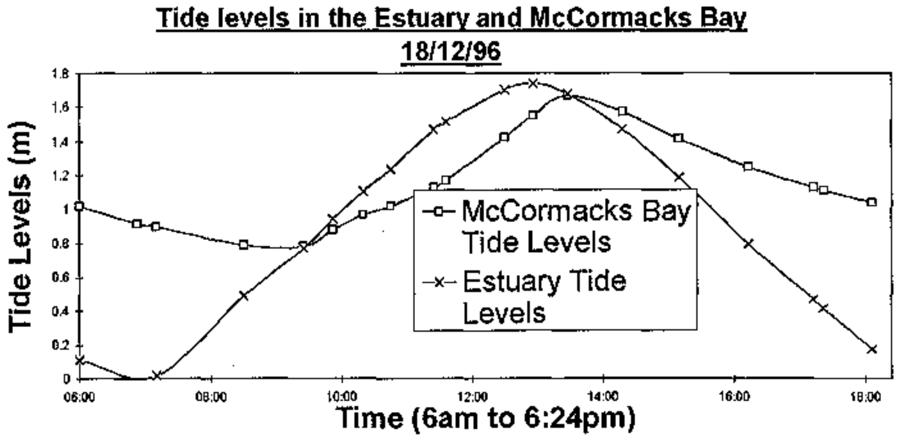
2.2 Equipment and experimental methodology.

Tide gauges and a manometer were used to measure and compare tide levels in the bay and the estuary additionally velocity measurements were taken with a two component electromagnetic velocity probe. The tidal gauge was erected in the bay in an area sheltered from the tidal jet which had considerable momentum and flowed with a peak velocity in excess of three metres per second. The difference in water level in the bay and estuary was measured using a differential manometer formed from plastic hose attached to galvanised iron stilling cylinders at each end. The readings were taken using a tube bent in an inverted U and difference in the level of the bay and the estuary were measured after air had been injected into the top of the U, with a hypodermic syringe.

The variation of the surface area of the bay with time was determined by taking a series of photographs froma view point above the bay.

2.3 Water Levels

The set of data used for this investigation was obtained on the 18 of December 1996, with a high tide of 2.1m and a low tide of 0.4m recorded at Lyttleton. The tidal records for the estuary and the bay can be seen in the **Figure 4 below**.



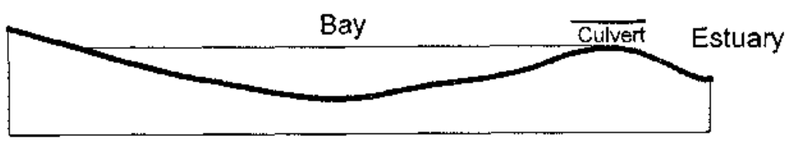
It can be seen that the tidal range in the bay is 0.88m and in the estuary is 1.74m

1. High tide at Lyttleton (12:04pm)
2. High tide in estuary (12:56pm)
3. High tide in McCormacks bay (1:28pm)

The relationship between tide levels in the estuary and bay can be established from the measured data. The bay levels run from just above the invert of the main culvert where flow out is restricted due to the causeway ***(see figure 5 below)*** until coincides with the estuary tide level just after the peak. It is expected that the phase difference between the tides would depend on the tidal range in the estuary.

Figure 5 below, shows the minimum volume retained in the bay

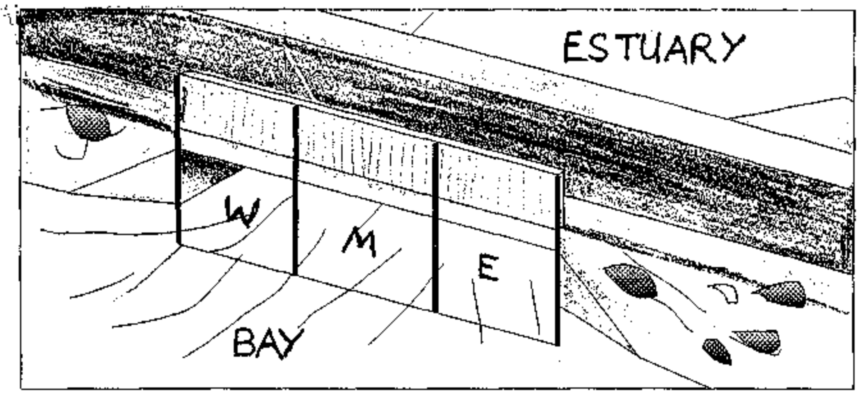
Exaggeration of water trapped in bay



2.4 Velocities

The velocities through the main culvert were very dependant on the flow direction and stage in the tidal cycle. They were measured at regular intervals and at three different points along the main culvert. Each measurement was representative of a third of the width, allowing more valuable estimates to be made of the flow rate.

Figure 6 below, shows the culvert and the western, middle and eastern sections.



As the estuary tide level approached the level of the culvert invert on the rising tide, the velocity through the culvert increased rapidly and established a jet which flowed into the bay. The flow rate increased rapidly until steady conditions were reached after two hours. Thereafter the flow velocities remained unchanged for approximately an hour and then decreased rapidly to the change in direction in an hour and a half. The flow regimes are seen more clearly in **Fig 7** where velocity magnitudes are shown over the tidal cycle.

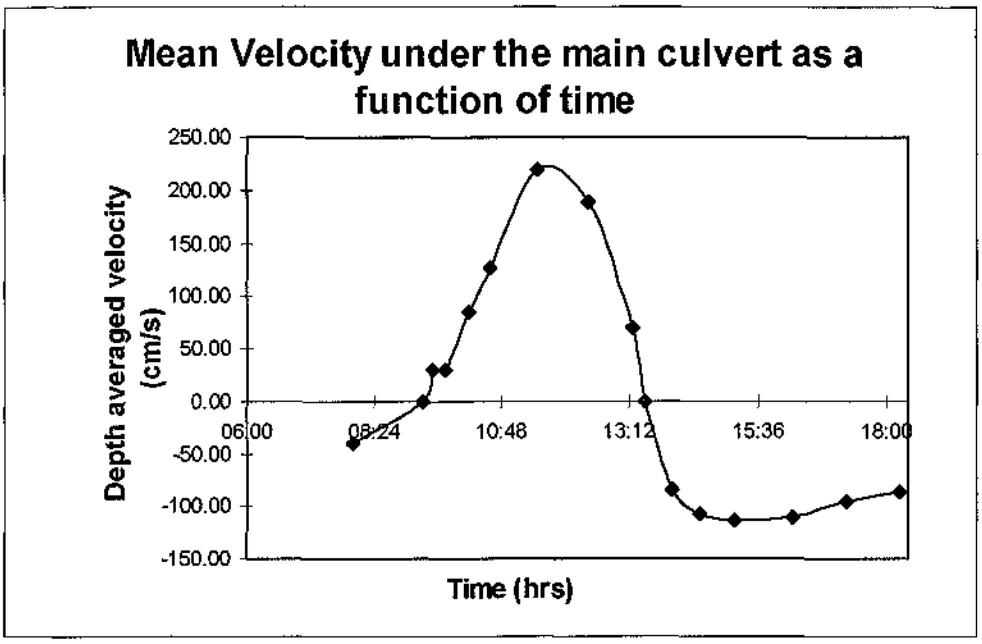


Figure 7 above, The velocity profiles of the three sections under the main culvert are shown. Negative flow direction is out of the bay.

The figure above shows that highest velocities occur during the flood phase of the tide. The velocity peaks at close to three metres per second and the variation with time is more symmetrical than was observed on the ebb tide. The outgoing tide's velocity profile is more skewed with velocities dropping off as the driving head reduces.

Figure 7 above is made up of the average of the velocities taken from the three sections under the culvert which can be seen in the figure 5 on the next page. The velocity (at all three sections) was measured over varying depths under the culvert. The velocities in the middle are slightly higher than those of the two adjacent sections, this is due to effects of friction being greater at the sides of the culvert.

All the velocity profiles exhibit the same trends with time as do the average values shown in figure 7.

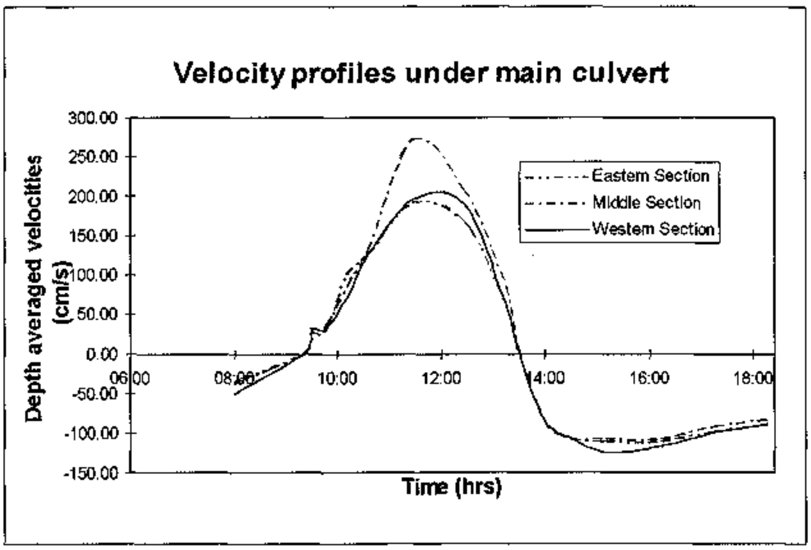


Figure 8 above, shows the depth averaged velocities for each of the sections under the main culvert.

The variation of the depth of water in the culvert with time was also recorded and the depths under the culvert are averaged due to the variation in channel bed profile. It can be seen that during the flood phase of the tide, velocities are higher then during the ebb which is of a longer duration.

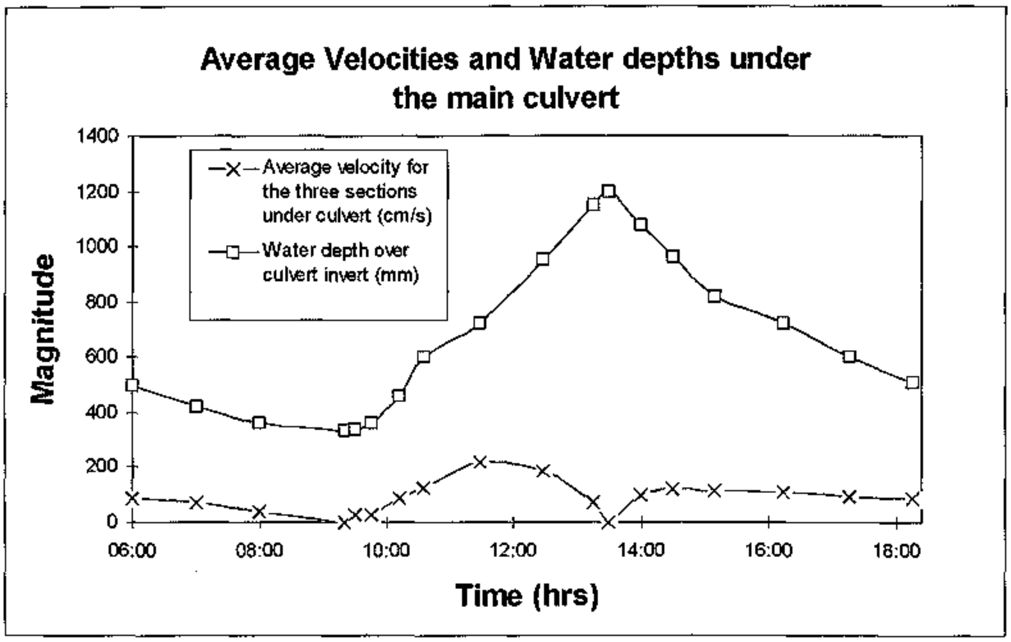


Figure 9 above, shows the average velocities and depths under the main culvert over the period of measurement. The velocities are shown as

absolutes with minimums correlating with maxima and minima depth in the culvert.

Continuity dictates the amount of water entering the bay during a tidal cycle must equal the amount of water leaving the bay to show a net balance in water entering and exiting the bay. The flow rates are obtained by integrating the measured velocities over the cross section of the culvert, and integrating these again with respect to time. Inthis way the tidal volumes entering and leaving were established.

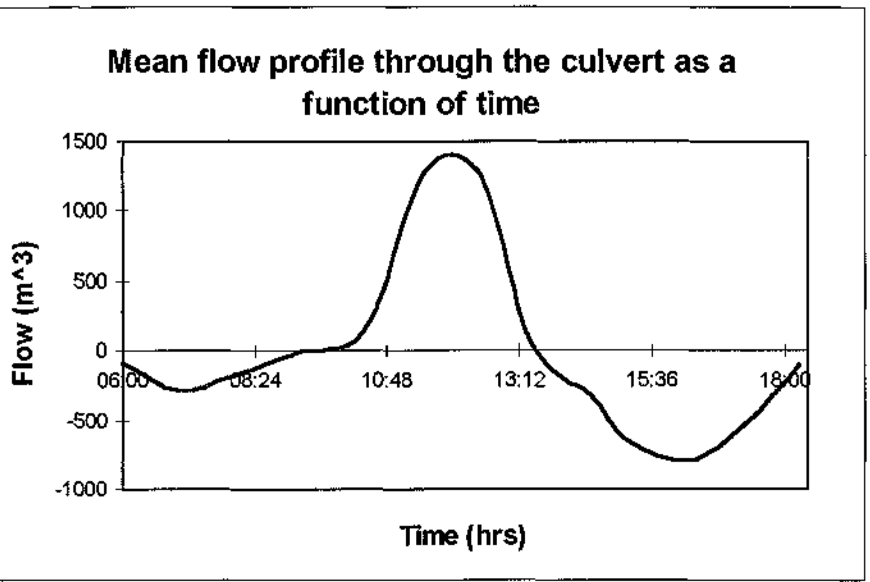


Figure 10 above, shows Q vs t (flow vs time) using time averaged flow rates over time. The area above the graph equals the area under the graph. That being the total inflow of water is equal to the total outflow.

3.0 Description of the hydraulic model

3.1 Flow Regime

Culverts are characterised by the variation of flow regimes. They can flow full or only partially full. In the case of the main culvert at McCormacks bay it is normally flowing only partially full. Full flow could occur during conditions of very high rainfall or during periods of extreme sea level.

The two basic regimes are subcritical flow through the culvert, and the other is when the flow passes through critical depth in the culvert in which case the culvert acts as a control of the flow rate (a hydraulic control). In the subcritical regime the tailwater depth (depth on the downstream side of the culvert) is such that the culvert control which might otherwise exist is flooded. Only when the tailwater drops to a level below that required to achieve critical flow through the culvert does the culvert itself become a hydraulic control. Once this occurs tailwater depths cease to play any role in affecting flow rate. This point of critical flow has its own characteristics and has a physical location or position in a flow. When subcritical flow passes through the control, it passes through critical depth and velocity when this happens it is said to past through a control. Critical conditions occur when the level is such that the potential critical depth is flooded in the culvert. Similar conditions will exist for a short time during a flood phase however the water level in the bay will rapidly increase to a point where the control is flooded out. After this there is a subcritical exchange through the culvert which is controlled by the differences in water level between the bay and the estuary. The separation of flow regimes runs through the critical and subcritical phases, critical being that where the flow is at a Froude number of 1. The regime of the flow determines the backwater shape and water surface profile through a control such as the culvert. The culvert acts both as a constriction and a weir. When flowing partially full there are three main flow regimes for normal culverts (ie without constriction) These are critical and subcritical flows on the ebb tide and subcritical flows on the flood tide.

3.2 Ebb Tide

The ebb tide differs from the flood tide by having two distinct regimes which are dependent on the elevation of the estuary relative to the constriction. Critical flow occurs when the tail water level on either side is below the level of critical flow in the channel for the upstream water level. Critical depth will be two-thirds of the upstream level.

3.2.1 Subcritical

During ebb conditions the flow direction changes from into the bay, to flow out of the bay as the water level in the estuary falls below that in the bay.. During the first phase of this flow out of the bay the change in elevation is insufficient to affect the flow regime and this drowns the flow remains in the subcritical flow regime. This can be classified as mild flow with the tailwater <u>above</u> critical depth. In this regime the water surface drawsdown over and through the constriction. The velocity of subcritical flow in the culverts comes from application of the Bernoulli equation between a streamline connecting the estuary and the bay and recognising the loss in energy between these two sections is due to the kenetic energy in the channel being dissipated by turbulence as it enters the estuary the same holding true with the flow in the opposite direction. In this regime the mean culvert velocity is given by

$$u = \sqrt{2g(z_b - z_e)/c_L} \tag{1}$$

where u is channel velocity, z_b - z_e is the difference in level in the estuary and in the bay, g is gravity, and c_L is the loss coefficient for the culvert.

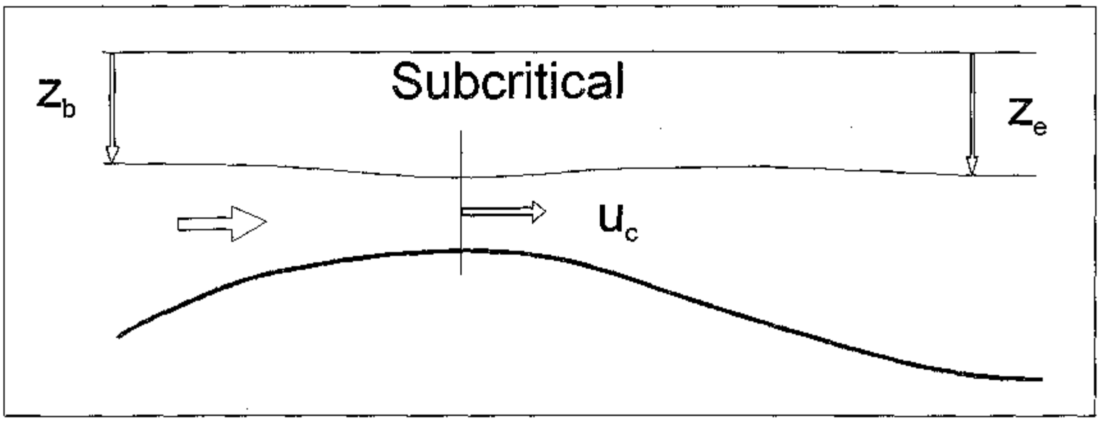


Figure 11 Above, Shows the profile of Subcritical flow through the main culvert.

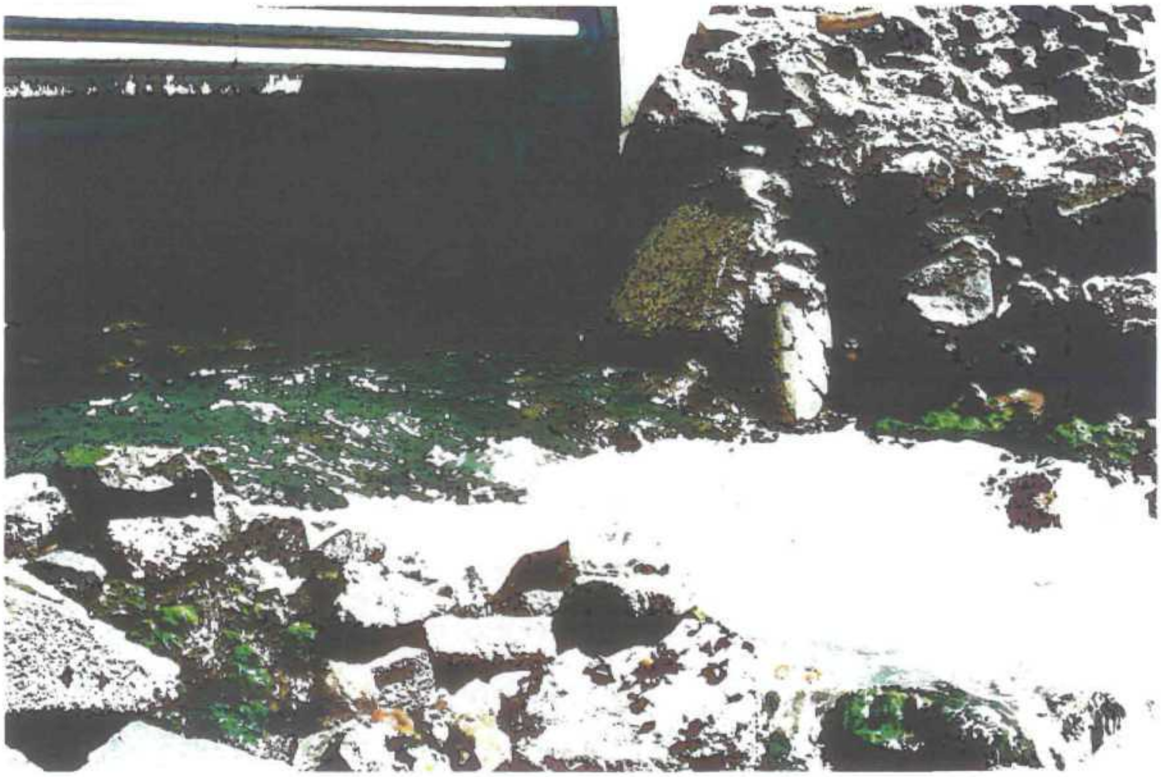


Figure 12 above, shows the culvert exit into the bay, water can be seen cascading down the rocky bed

3.2.2 Critical

This flow regime is characterised by the culvert becoming a hydraulic control so that flow passing through the culvert passes from subcritical through critical to supercritical. ***(See figure 12 above)***.

The velocities at the section of critical depth shown in the diagram as y_{cr} are given by Henderson (1966)

$$u_{cr} = \sqrt{g y_{cr}} \tag{2}$$

and then using the relationship derived from the energy equation

$$y_{cr} = \tfrac{2}{3} H \tag{3}$$

Where H is the total energy of the flow

The derivation from the energy equation is shown below.

For ebb flow

For ebb flow

If $z_E > y_c$ where $y_C = \frac{2}{3} z_B$ then flow in the culvert will be subcritical and determined by the difference in surface levels of the bay and the estuary which is $z_B - z_E$

If $z_E \le y_C$ then the culvert will act as a control and the flow rate will be independent of z_E and $u_C = \sqrt{g \cdot y_C} = \sqrt{\frac{2}{3} g \cdot z_B}$ (4)

Where u_C = the critical velocity

y_C = the critical depth

g = the gravitation constant (9.81m/s/s)

z_E = level in the estuary

z_B = level in the bay

Which comes from the relationship

$$\frac{u_C^{\,2}}{g(h_C - z_C)} = \frac{u_C^{\,2}}{g y_C} = 1 \tag{5}$$

(Froude Number)

h_C = the height of the culvert

Applying the Bernoulli equation between sections upstream (B) and downstream (E) of the culvert, (see figure 13). gives

$$H_B = H_E + H_{Losses} \tag{6}$$

H_B and H_E are the hieghts in the bay and estuar respectively, and H_{losses} or H_L is the head loss or energy losses.

Where

$$H_L = c_L \left(\frac{u^2}{2g} \right) \tag{7}$$

c_L = the loss coefficient

for Head loss due to energy

gives

$$u = \left[\frac{2g}{c_L} z_B - z_E\right]^{\frac{1}{2}} \qquad (8)$$

the energy equation also applies at the critical depth i.e. at the cross section in the flow that is critical, at this point $H_B = H_C$ (H_C is the critical hieght) so that

$$z_B = \frac{u^2}{2g} + y \qquad (9)$$

z_E must equal y if all of the K.E. (Kinetic Energy) is to be dissipated

$$\text{but } Q = uby \Rightarrow z_B \frac{Q^2}{2gb^2y^2} + y \qquad (10)$$

Q = the flow rate m^3/s and b is the width (bredth of the culvert)

or

$$Q = 2gb^2y^2(z_B - y), \qquad (11)$$

for any value of z_B, there is a given maximum value of Q, which can be found by

$$\text{putting} \quad \frac{dQ}{dy} = 0 \qquad (12)$$

or

$$\frac{dQ}{dy} = \left(2gb^2 2yz_B - 3y^2\right) = 0\,, \qquad (13)$$

which becomes $y = \frac{2}{3} z_B$ if z_E falls to a point which would require that $y < \frac{2}{3} z_B$ the required flow with $y = \frac{2}{3} z_B$ develops in the channel and z_E ceases to affect the flow rate.

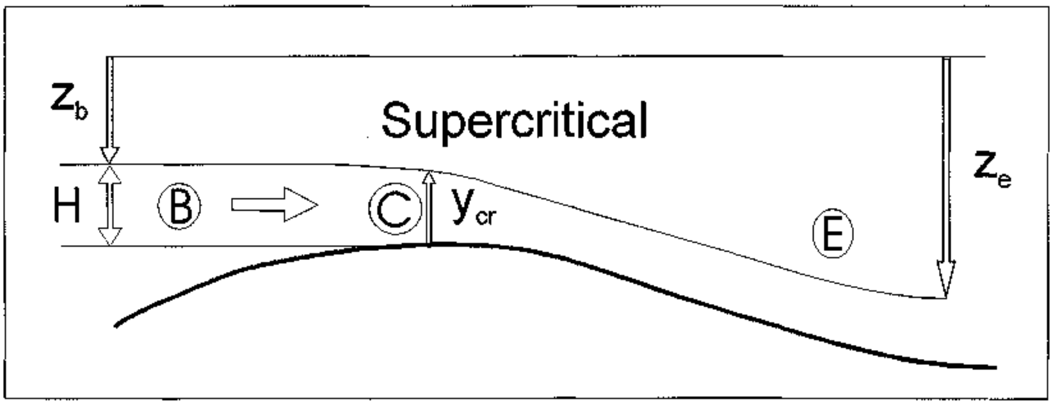


Figure 13 Above, Shows the supercritical flow on the outgoing tide, flow passing the critical depth and passing out over the rocks into the estuary. Sections B, C and E are shown as mentioned above.

3.3 Flood Tide

3.3.1 Subcritical

During the flood phase the flow is passing back into the estuary. In this regime differences between the levels in the bay and the estuary are less than in the ebb phase. This denies the ability of the tail water to drop below critical depth. It is in this flow regime that a significant jet opens up after the constriction of the culvert. **Figure 14 below, shows the jet coming into the bay.**

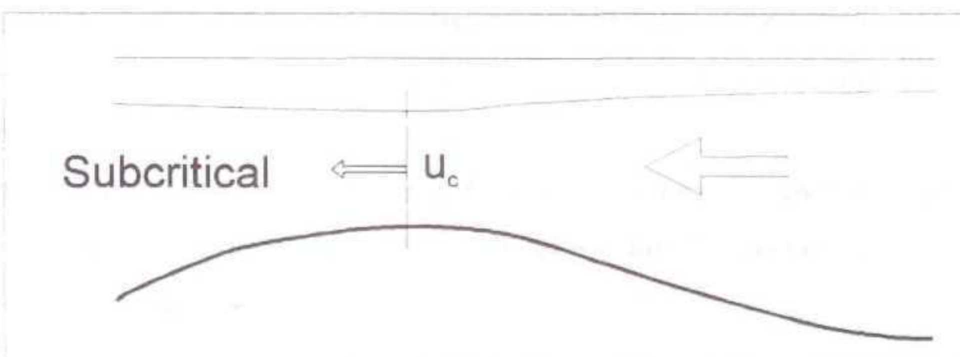


Figure 15 Above, Shows Sub-critical flow on the incoming tide with flow coming into the bay.

3.4 Model Type

A spreadsheet routine was used to solve the previous equations, test for the appropriate regimes and determine flow rates and water levels. A second order Runge-Kutta iterative routine was used to solve the governing differential equation as described below. This was done for each time step, first using an approximation of the flow characteristics from those known, ie the tide profile shape, magnitude and length combined with the known critical characteristics of the culvert for a given flow. From this first approximation a second estimate is made by comparing the difference in potential characteristics to those of the second estimation thereby giving a closer result.

3.4.1 Determination of Z_B with Time

The level in the bay can be found by using the continuity equation. This enables the relationship between the variation of Z_B with time to be found.

$$Uby = \frac{d}{dt}\left(A_B z_B\right) \qquad (14)$$

The flow into or out of the bay equals the rate of volumetric change within the bay which we can then evaluate $A_B = fn\left(z_B\right)$ with the function relating A_B and Z_B being obtained empirically from the photographs of the bay surface area. The coninuity equation was solved by using a second order Runge Kutta iteration routine.

3.4.2 Formulas used in the model described above

The theoretical relationships used to describe the behaviour of the bay as described previously were than solved numerically in the model by the following equations;

Eqn 4, The relationship between A_B and Z_B was obtained empirically from the bay surface area data, and an equation of the form of equation 15 was fitted to this data and α,β were evaluated.

$$A_B = \alpha Z_B{}^{\beta} \qquad (15)$$

A_B = the area of the bay, α, β = constants used in power relationship

Eqn 15, This is the equation used to simulate the estuary tide profile from basic tide parameters such as high and low tide levels and the time for each tide.

$$Z_E = Z_{E0} + \frac{A_0}{A_1 + A_2}\left[A_1\theta^{½} + A_2\theta^2\right]\cos 2\pi \frac{t}{T} \tag{16}$$

Where $\theta = \left[\frac{t}{T} - INT\left(\frac{t}{T}\right)\right]$ and T = tidal period

Where A_0,A_1 and A_2 are coefficients used in fitting the generated sinusoidal wave shape to the shape of the tide level profile of the estuary.

Eqn 16, This equation is derived from continuity with the rate of change in bay level being dependant on the velocity in the channel, differences in water level and the area of the bay at that time.

$$\frac{dZ_B}{dt} = B_C(H_C - Z_C)\frac{u}{A_B} \tag{17}$$

Eqn 7, The velocity head in the channel is dissipated in the estuary therefore

$$Z_C = Z_E \tag{18}$$

Eqn 19, From Eqn 18, applied to the levels in bay and estuary

$$(h_C - Z_E) = y_C > y_{Critical} \tag{19}$$

Eqn 20, From eqn 8, shown in section 3.2.2

$$u_C{}^2 = \frac{2g}{c_L}(Z_E - Z_B) \tag{20}$$

Eqn 21,if the Froude number = 1

$$\text{then} \quad y_{Critical} = \tfrac{2}{3}(h_C - Z_B) \tag{21}$$

Eqn 22, Continued from Eqn 20 re-arranging the variables gives

$$u_{Critical} = \sqrt{g \cdot y_{Critical}} \tag{22}$$

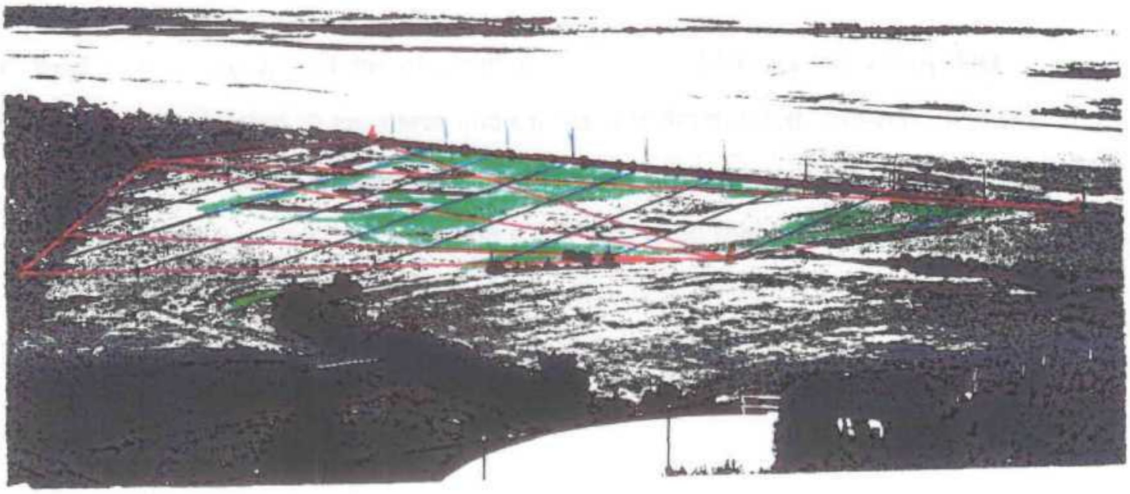
4.0 Model Calibration

A spreadsheet model was developed to predict the tidal response characteristics of the bay to variation in the estuary. For this a collection of the measured data must be used. The tidal cycle varies between 12.4 hours and 12.6 hours with the tidal range varying from upwards of 2m to below 1m from spring to neep conditions. Basically the significant similarities would have to be in velocity characteristics and the levels of the bay and the estuary.

4.1 Bay Area - Water Level

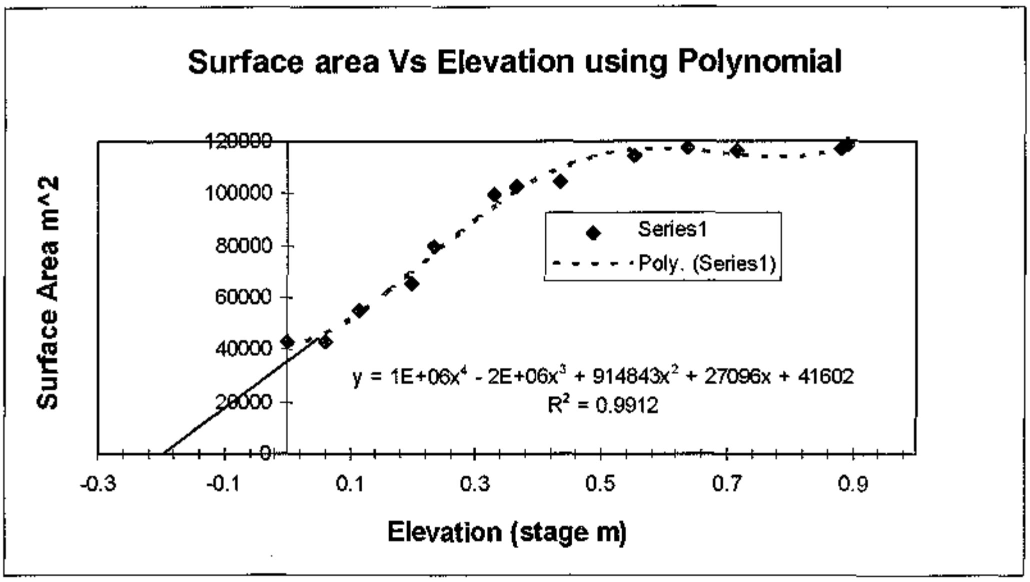
The wetted surface area of the bay was estimated at various phases of the tide using the series of photographs taken from a vantage point above the estuary as shown in figure 16 below. Landmarks identified on the photographs these were surveyed, and a grid formed. The perspective image in the photographs was converted to an undistorted plan view of the water and surface, Its area was then evaluated. This enabled the relationship between tidal stage and the wetted surface area of the bay to be established. Thirteen photos were taken of the main bay on the 18th of December and a further six were taken later. The photos taken later were linked with the photos taken on the 18th by calibrating them against the depth of water in the 1.2m diameter eastern culvert. The grid used was one of triangular segments cut by a series of straight lines corresponding to the street lights on the causeway.

Figure 16 Below, this shows the grid as set up for interpreting surface areas from tide levels recorded. This view shows the main bay and the second figure below shows the same grid setup for the eastern bay.



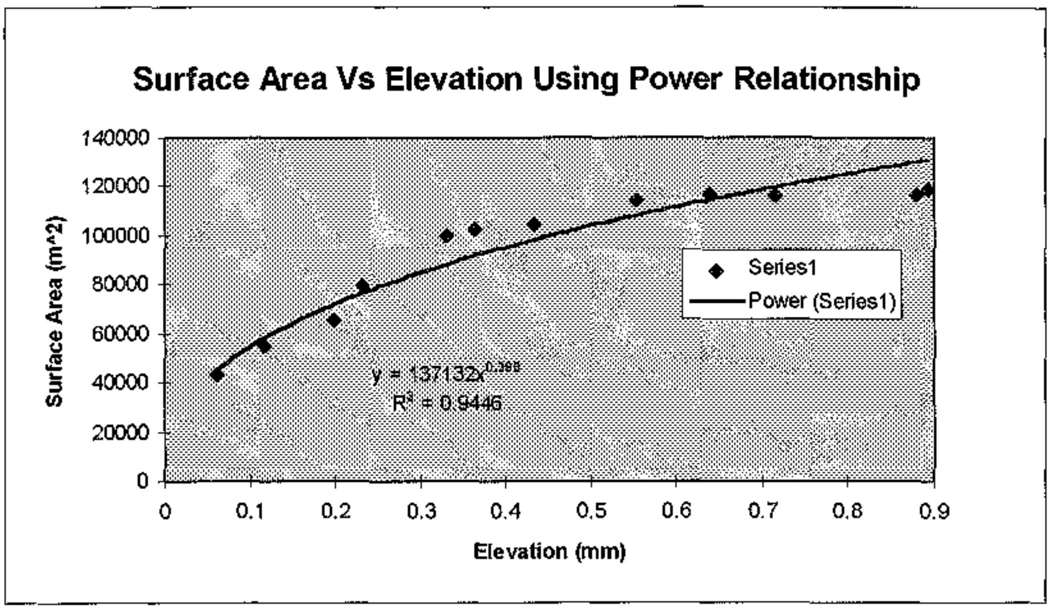
These measurements provide a relationship between tidal stage in the bay (Z_B) and depth and surface area of the bay. The data was tabulated on a spreadsheet and a power curve regression was used to determine the relationship expressed in equation 15. The power relationship, allowed the prediction of a surface area based on a measured depth. The relationship between stage and surface area was determined so the volume of water in the bay could be evaluated given a rate of change of surface level, therefore the rate of volumetric exhange in the bay could also be determined. There were, however, some complications, as the surface areas for a given depth on the outgoing tide were not equal to with those of the incoming tide. This can been seen to come from the drainage of pools of water on the tidal flats which occurs over time during the ebb tide, but these are quickly filled in buy the flood tide.

Figure 17, Below shows the relationship between elevation and surface area, related using a polynomial



In order to estimate the volume of water at low tide, not having the survey data. The stage extraplolated to zero area and the volume determined between the invert of the channel and the point of zero depth. By extending the trendline to intercept the negative x-axis in this case elevation it has estimated that the zero wetted surface area occurs at an elevation of -0.2m. That is 0.2m below the minimum level in the bay, from this estimate the volume in the bay can be estimated as can the percentage flushing of the bay during a tidal cycle.

Figure 18, Below shows the same relationship again but with a power relationship.



The polynomial fit, best models the actual bay behaviour, but the power relationship is easier to apply and still has an R^2 value of 0.9446 the latter would seem to acceptable for use in a model approximating the behaviour of the bay. The relationship used being (from equation 15)

$$\text{Surface area} = \alpha(\text{the bay level})^{\beta}$$

$$\alpha=137000$$

$$\beta=0.4$$

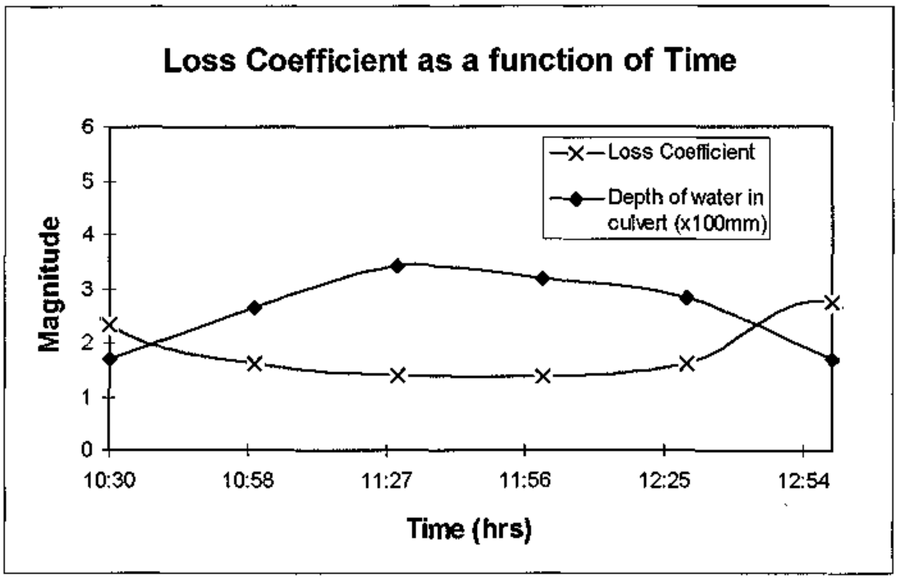
4.2 Loss Coefficient

The main culvert located just west of the rock-spur carries the majority of the tidal water.. It is the ratio of the kinetic energy dissipated by friction in the jet leaving an obstruction to the mean kinetic energy of flow in the obstruction. The magnitude of the loss coefficient can be determined direclty from the measurements of water surface levels and flow through the culvert. This loss coefficient is made up of three factors firstly frictional losses in the culvert and the dissipation of kinetic energy in the jet issuing from the culvert. The later two of these are grouped into a general loss term given by

$$h_b - h_e = c_L\left(u^2 / 2g\right) \qquad \text{Eqn(22)}$$

The dominant component of the losses is the kenetic energy of the flow, which is not recovered after flow through the constriction. From calculation of the loss coefficient on a spreadsheet the results showed that when the flow evened out on the flood tide the loss coefficient settled to values in the range of 1.3 to 1.6 which seem reasonable when a third is subtracted for frictional losses. From this a value of 1.3 was used in the model.

Figure 19 below, shows the Loss Coefficient compared with velocity



4.3 Estuary Tide

By using the equation shown below the shape characteristics can be altered to best fit the observed behaviour of the bay and estuary's tide levels.

$$\eta = \frac{A_0}{(1+A_1)}\left[\left(1-\left\{\frac{t}{T}\right\}\right)^2 + A_1\left(1-\left\{\frac{t}{T}\right\}\right)^2\right]\left(1-\cos 2\pi\left\{\frac{t}{T}\right\}\right)$$

$$Z = \frac{Z_0}{A_1 + A_2}\left\{A_1\left[\frac{t}{T} - INT\left(\frac{t}{T}\right)\right]^{\frac{1}{2}} + A_2\left[\frac{t}{T} - INT\left(\frac{t}{T}\right)\right]^2\right\}\left(1-\cos 2\pi\frac{t}{T}\right)$$

By altering the shape characteristics of the equation above and then superimposing the tidal records measured a comparison can be made.

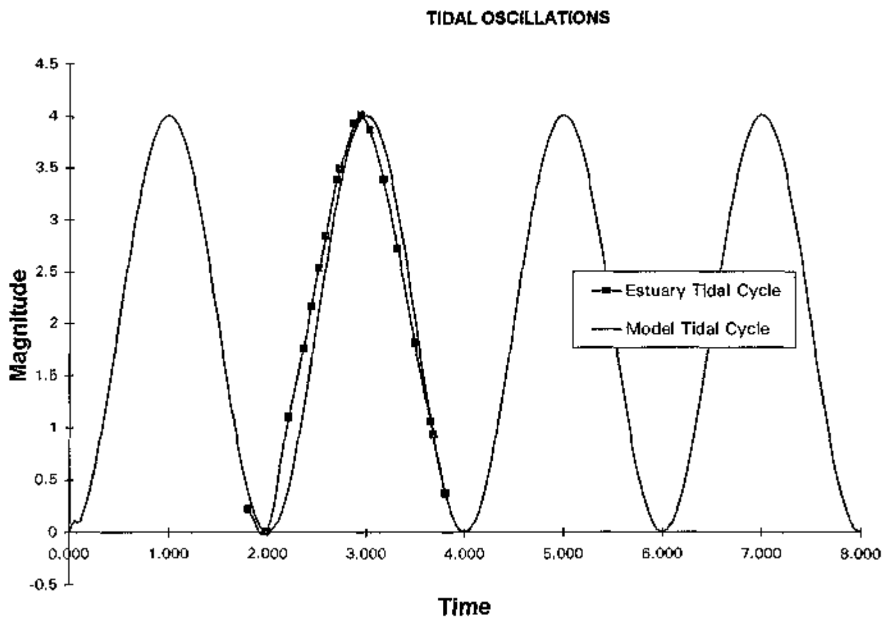


Figure 20 above, shows the estuary tidal profile compared with a generated sinusoidal wave

4.4 Comparison of observed response with calibrated model

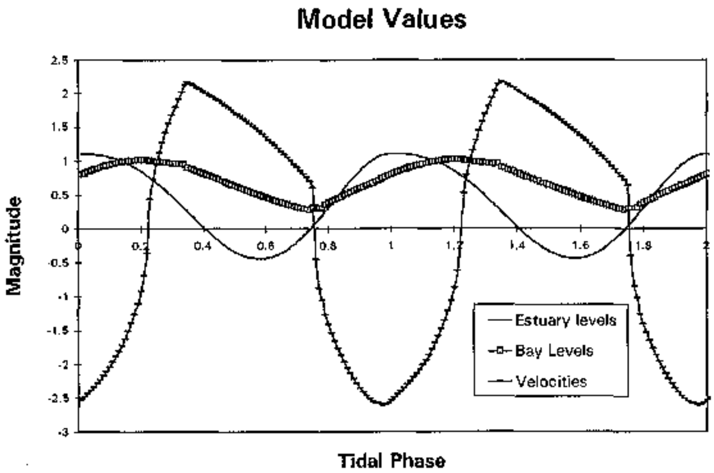
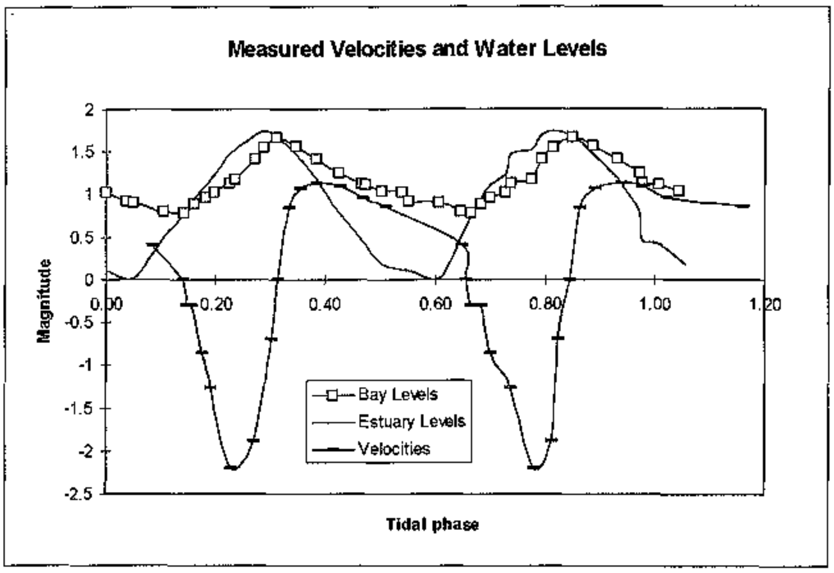


Figure 21a Above, a computer model of the characteristics of the bay over a 2 tide sequence. As compared with the measured values in Figure 21b Below.



The Computer model output in figure 21a compares favorably with the measured data in figure 21b, The peaks for velocities are very close and the tidal ranges though not exact, are also very similar. The models output gives higher values overall for velocity in both directions, and these would give slightly higher values for water level range in the bay. This noted the change in bay water levels found with altering the depth of the culvert were significant and could not solely be explained by the higher velocities given in the model. For comparison of these results with those of the trial culvert depths and widths see appendix C.

5.0 Hydraulic Management Options

5.1 Existing Condition

The tidal prism of the bay for the tidal range of 1.8m is 82,000m^3. From the zero value found in section 4.1 the volume of water retained in the bay was 12,600m^3 as compared with a combined total of 103,200m^3. In terms of the above figures approximately 88% is flushed from it each tidal cycle.

5.2 Options

The main problem at the moment is how to control the odour and weed problem that is occurring in the bay without radically changing the already altered ecosystem. At the moment, the natural flow in the bay has been cut off by the construction of the causeway and the addition of added nutrients from the Bromley sewage treatment facility, the sheltered nature of the bay and the lack of flushing enhance the environment for marine algae's to grow. The dead algal material produces a zone of slime, stopping oxygen from getting beneath it and inhibiting shellfish and other sub-surface species from growing and living under it.

There are many options for control of the odour problem now occurring in McCormacks Bay. These include completely infilling the bay (ie reclaiming the inlet), dredging the shallow parts of the bay to give approximately 1m of water cover at low tide, and increasing the tidal circulation by the introduction of one way tide gates which permit flow only in one direction, therefore allowing flow into the bay at one point and then out of the bay at another point. If these gates were located at the western and eastern ends of the bay then the circulation could be improved dramatically.

There are other physical aspects of the location of the bay which contribute to the problem. It is located on the southern boundary of the estuary which receives a considerable amount of the available sunlight and is sheltered from the easterly winds which generate much of the wave activity in the estuary and along the coast during the summer.

5.2.1 Widening the inlets (increasing the tidal flushing)

A hydraulic study undertaken by the Christchurch Drainage Board (Carver, 1981) studied the implications of developing a new culvert under the causeway that now exists. The study showed that the a new culvert would not in fact increase the currents inside the bay by any reasonable margin. In fact the increased currents and the resulting temperature reduction were of such small magnitude that is has become obvious that dramatic increases in the available opening apertures would be necessary to yield even modest increases in the flushing of the bay. By testing the model using various sizes for the culvert it was discovered that an increase in the depth would allow for better drainage by increasing the range of levels in the bay.

Table 1 below, shows the relative increases in bay level range from increased width and depth in the culvert. The figures given are results from the iterative model used.

h_C	B_C	Z_{max}	Z_{min}	H_b
1.7	6	1.668	0.781	0.88
	12	1.67	0.78	0.89
2.5	6	1.70	0.62	1.08
	12	1.70	0.58	1.09

The results above show dramatic benefits from deepening the culvert. By increasing the depth of the culvert to 2.5m the range of water levels in the bay increases by 23%. Further studies would be advised to perfect the model and check its results.

It would be possible to insert large gates at the western and eastern ends, enhancing the tidal flow's ability to flush and mix better within the bay. The use of one way water gates, would increase this even further by forcing significant flow across the bay between the gates. Complication and maintenance issues however, rule out their use. There is also the problem of the sheltered nature of the bay which cannot be remedied at all. It seems that the existing situation would probably exist at a lower magnitude even without the causeway having been constructed.

5.2.2 Dredging the whole bay

Initially this option would seem to present the least feasible solution, but deepening the bay may be the only practical way of reducing the algae problem without filling the bay in. The dredging process would need to lower the present bed levels in the estuary by up to a metre, therefore minimising the exposure time to the sun for the shallow groupings of Algae. Only those areas currently presenting an odour problem would need to be dredged, though which would significantly reduce the costs involved. There are, however, some foreseeable problems which might occur. One of these would be the transportation of the algae and sea lettuce, the major odour causing problem, to areas which until now have been relatively free of the problem. Such problems could occur in the southern part of the bay where stormwater input has thus far discouraged the proliferation of sea lettuce. The dredging of the bay would alter the bay's temperature characteristics and this could contribute to the migration of the problem to another part of the bay. The dredging would also have to take into account the dynamics of bed form change due to currents and sedimentation from stormwater inputs as well as future reclamation and recreational use, and for the marine and bird life which have become accustomed to the present characteristics in the bay.

Disturbance of sediments in the bay also presents a problem, as at the present time they act as a sink for nitrogen-based nutrients. Release of these nutrients at critical times of algal growth could be particularly disastrous. Changes in currents as well as dredging could both result in an increase in nitrogen levels, and even if the nitrogen-rich brine could both be flushed from the bay, it would still enter the estuary and have a profound effect on the species living there.

Dredging would have to be completed with this fact in mind as even the use of modern suction dredges would still produce significant suspended sediments and elevate nitrogen levels. There is also no route by which a floating dredge could avoid being beached by the tide, so therefore would have to be supported.

There have been many engineering proposals put forward for flood control in the estuary. In a report on the ecology of the Avon Heathcote estuary (Knox and Kilner 1973) the effects of dredging activity on the ecology of the bay was discussed. The schemes discussed involved the formation of channels by dredging to allow the two river tributaries to flow directly out to sea. This is similar in concept to the idea of dredging the bay to keep the exposure time of the algae within bounds. The dredging of channels to promote flushing of the bay during tidal exchange has also been suggested, but this would seem to be of little consequence and would drain the flats quicker after they had been exposed.

The effects discussed by Knox and Kilner (1973) encompassed the whole estuary and though we are concerned with only McCormacks Bay, effects on one can be compared to probable effects on the other. The possible effects were broken up in to the following section:

- Salinity
- Exposure times
- Algal growth
- The sediment biota
- Current velocities
- The birds

The overall effect of the dredging can be summed up as;

- Exposure times at the various tidal levels would generally be increased due to the fact that the channels would contain more water and would drain quicker.
- The current velocities within the channels would increase and hence have a greater effect on the sedimentation process by removing sand.
- Dredged channels would allow greater salinity penetration and thus increase salinities further up the estuary, though predicted salinity changes were low. This is interesting when compared to the effects of the Woolston cut on the plant life in the Heathcote river.

From these general effects on the estuary consequent effects on the biota within would be;

- Reduced algal production due to increased exposure times.
- Dramatic effect on the benthic invertebrates. Dredging would involve physical removal of the animals and deposition of sediment. The fine anaerobic muds located just under the surface would kill animals. These effects as well as the changed physical characteristics of the estuary (including currents and particle size) would lead to changes in both the number and distribution of animals. The

increased exposure would also leave fewer places for inhabitation by these animals.

- The increased exposure time coupled with the reduction in oxygen levels in the water due to sedimentation would have a profound effect on the numbers of fish and other aquatic life especially to young sand flounder.
- The increases in exposure times across the mudflats and the rapid drainage would decrease the amount of food available to wading birds and the time available for feeding.

This study viewed the main problems of McCormacks Bay as being a lack of tidal flushing, dam impoundment of water in eastern part of the bay by the rock spur and eutrophication of the bay. It was recommended that no further reclamation should take place and that increased flushing might remedy the eutrophication problem. As has already been discussed, the problem of increasing flushing would involve considerable effort and precise construction to produce an effective gate or culvert system.

5.2.3 IN-Filling or Reclaiming the bay

Reclamation of part or all of the bay would seem to be a very drastic measure but would definitely reduce the odour problems currently encountered. The estuary's shaping process is very slow and would most development would probably occur during sea storm events (i.e. 100-500 year storm events). This would give a delayed reaction to the discontinued flushing. Problems could also be encountered with drainage from the heavy sediments which are currently forming the bay.
The obvious drawbacks of this solution are the destruction of a habitat and recreation area. The reclamation would also destroy the aesthetic value of the bay for the surrounding residents. The importance of the bay as a habitat is generally overlooked due to the restricted nature of the food sources available to birds and grazers, but it does provide an important wet sanctuary from the easterly wind and can also provide a warm area with a selection of food for most birds. Distance between areas of sanctuary can affect certain species of birds, some of which are found in the estuary. The in-filling of the bay would result in greater distances between equivalent sheltered areas in the southern part of the estuary. This would

in fact reduce the numbers of those bird species in the estuary, particularly in its southern part.

The reclamation of the bay could provide the community with additional land area and this could be used as the reclamations to the west have been used by a kindergarten and a community centre as well as a local squash club. The community would probably support partial reclamation (like that which has happened sporadically since the early eighties) as this would seem to provide options for better road access to the new and expanding subdivisions on the surrounding hills.

6.0 Discussion

To summarise the main issues with bay as it is;

- Lack of tidal flushing due to the construction of the causeway
- lack of surface and filter feeders
- too much algae in water not conducive to allowing easy movement of fish
- Odour and aesthetic problems with decaying and dominant algae
- siltation of the bay from storm water inputs
- changing needs from the surrounding inhabitants - exclusive suburbs
- elevated nutrient concentrations in the sediments

There are the same algal problems along Humphrey's drive leading to odour problems.

From Knox and Kilner (1973) it can be seen that in times of low algal activity in the estuary as a whole there are still considerable concentrations within McCormacks bay.

It seems as if the causeway may have enhanced migration of the algae within estuary to the bay but it is probably not the cause of the algal problems which are likely attributable to the changed nutrient levels in the estuary since large scale inhabitation.

Derek Carver (formerly of the Christchurch Drainage Board now of the Christchurch City Council) believes limited dredging may have the effect of keeping the algae in problem areas underwater permanently or for considerably longer than is the present case. This would decrease the exposure to direct light and reduce their growth.

The comment has been raised that increasing the flushing capacity of the bay would make a significant change to algal populations in the bay. The only aspects that can be changed in reality would be with either dredging or filling in the bay. The possibility of increasing flushing cannot be implemented easily, and may not be possible. The use of tide control gates may increase flushing but they present their own maintenance problems. The deepening of the culverts has been shown with the use of a model to increase the range of levels within the bay. This may present an option, but it must be investigated further.

Of the two other options limitations from concerned rate payers about the bay's environment have already stopped the possibility of filling it in completely. The issue of the importance of the bay to the estuaries ecology has also to be looked into. As a sheltered, well sunned, shallow bay it provides habitat options for the birds and wildlife in the estuary it would seem to be an important link in the ecosystem and therefore this would in itself preclude its destruction.

The second option that of dredging the bay also seems to be risky, not only are there elevated nutrient levels in the estuary water at present, These due to effluent input from Bromley, there is also high concentrations in the sediments left by decaying and rotting algae. Stirring up of the these nutrients may in fact trigger an explosion of growth in the bay and the estuary. The increase in depth in the bay might have a considerable affect on the growth of algae but this would have to be conclusively proven before such activity could go ahead. As well as effectiveness on the algae growth a close observation would have to be kept on the effects on other parts of the ecosystem. It must be kept in mind that this would be a remedial action to help control a problem, that would seem to have come from actions in the past. It would be very wise not repeat the mistakes of the past and damage the ecosystem in another way.

The options described seem to be limited and costly but are there to be taken if the problem becomes a big enough issue which given the affluence of the inhabitants of the surrounding subdivisions would seem to be a high probability.

7.0 Conclusions

The behaviour of McCormacks bay during a tidal cycle, can be broken down into separate components which can be duplicated in equations and combined with known flow regimes to form a model. This model can then be calibrated against measured data collected in a complete tidal cycle. With the model calibrated an accurate empirical estimate can be made of the levels in the bay given the tide levels in the estuary.

The results show that the bay can be modelled with a degree of accuracy. The different characteristics can be incorporated into a model. With this it was found that by modifying the culvert characteristics of the culvert the range of water levels could be increased. This would have beneficial effects on the flushing of the bay almost completely draining the bay on the ebb tide.

The relative merits of dredging and completely in-filling the bay were discussed and shown to have faults which would have to be dealt with. The dredging would allow better drainage and could remove some of the de-oxygenated silt, but this in turn would introduce nutrients from the sediments into the bay. The other option of in-filling the bay completely would completely eradicate the algae problem from the bay, but this is unreasonable to the inhabitants of the homes surrounding of the bay. Further investigation into the feasibility of increasing the flushing by altering the culvert, and also of dredging the sediments in the bay should be undertaken. With the options carefully weighed up, it is important that one or some of them be partially or fully implemented.

8.0 Bibliography

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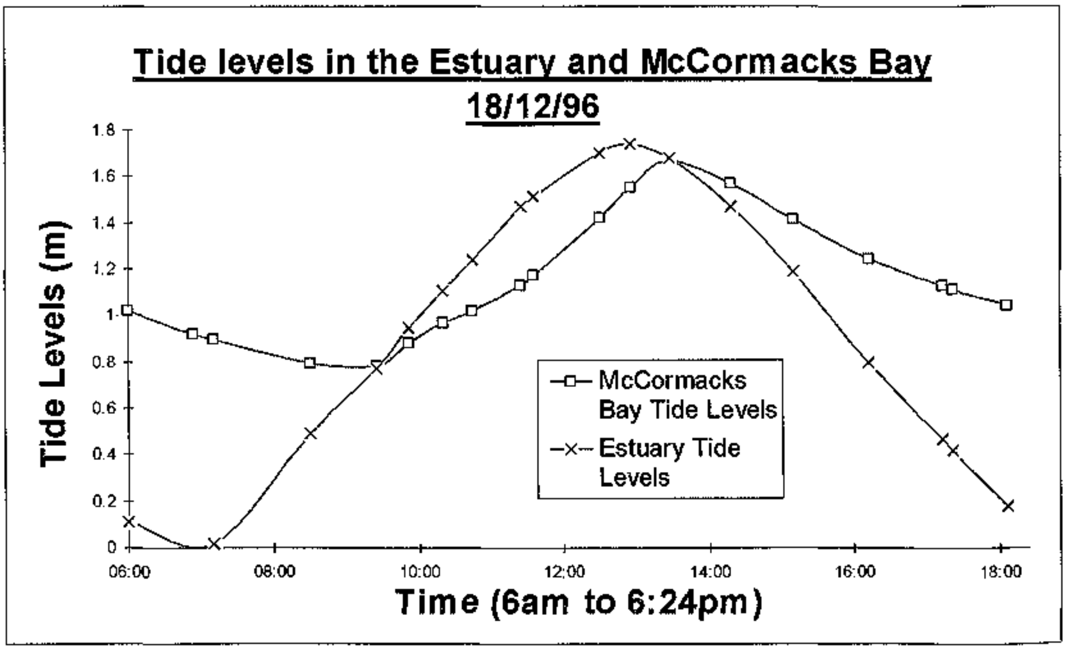
Appendix A

Much of the data presented in this report is the results of calculations and tabulation completed on spread sheets. The following are the calculation tabulations, and graph from which these results were found.

Water Levels

Bay Time	Bay Gauge	Bay Abs	Estuary Time	Estuary Gauge	Estuary Abs
06:00	18.15	1.02	06:00	17.24	0.11
06:53	18.047	0.917	07:10	17.148	0.018
07:10	18.028	0.898	08:30	17.621	0.491
08:30	17.92	0.79	09:25	17.9	0.77
09:25	17.911	0.781	09:52	18.075	0.945
09:52	18.01	0.88	10:20	18.236	1.106
10:20	18.098	0.968	10:45	18.367	1.237
10:45	18.15	1.02	11:25	18.6	1.47
11:25	18.26	1.13	11:36	18.645	1.515
11:36	18.3	1.17	12:30	18.833	1.703
12:30	18.55	1.42	12:56	18.87	1.74
12:56	18.68	1.55	13:28	18.808	1.678
13:28	18.798	1.668	14:18	18.602	1.472
14:18	18.7	1.57	15:10	18.317	1.187
15:10	18.544	1.414	16:13	17.926	0.796
16:13	18.376	1.246	17:13	17.6	0.47
17:13	18.26	1.13	17:22	17.546	0.416
17:22	18.24	1.11	18:06	17.305	0.175
18:06	18.17	1.04			

The table above contains the water level measurements and the graph below show the water levels as a function of time



Velocity Measurements on the 18/12/96
McCormacks Bay main culvert

Time (24hrs	section	Vel. x-dir Cm/s	Vel. y-dir Cm/s	SRSS	depth mm	0.?d	Avg. Vel. Cm/s	Area m^2	Flow Est. m^3/s	
08:00	1.00	14.000	12.000	18.439	300.000	0.200		0.615	0.000	
		3.000	48.000	48.094	300 000	0.800	33.266	0.615	0.205	
	2.00	0.000	32.000	32.000	420.000	0.200		0.861	0.000	
		8.000	42.000	42.755	420.000	0.800	37.378	0.861	0.322	
	3.00	0.000	50.000	50.000	360.000	0.600	50.000	0.738	0.369	**0.895**
09:30	1.00	0.000	27.000	27.000	300.000	0.600	27.000	0.615	0.166	
	2.00	-3.000	32.000	32.140	420.000	0 600	32.140	0.861	0.277	
	3.00	3.000	30.000	30.150	270.000	0 600	30.150	0.554	0.167	**0.610**
09:45	1.00	0.000	27.000	27.000	300.000	0.600	27.000	0.615	0.166	
	2.00	0.000	32.000	32.000	420.000	0.600	32.000	0.861	0.276	
	3.00	0.000	30.000	30.000	270.000	0.600	30.000	0 554	0.166	**0.608**
10:12	1 00	0.000	100.000	100.000	450.000	0.600	100.000	0.923	0.923	
	2.00	0.000	85.000	85.000	540.000	0.600	85.000	1.107	0.941	
	3.00	0.000	71.000	71.000	420.000	0.600	71.000	0.861	0.611	**2.476**
10:35	1.00	0.000	125.000	125.000	600.000	0.600	125.000	1.230	1.538	
	2 00	0.000	115.000	115.000	630.000	0.200		1.292	0.000	
		0.000	145.000	145.000	630.000	0.800	130.000	1.292	1.679	
	3.00	0.000	125.000	125.000	570.000	0.600	125.000	1.169	1.461	**4.677**
11:29	1.00 .	0.000	185.000	185.000	720.000	0.200		1.476	0.000	
		10.000	200.000	200.250	720.000	0.800	192.625	1.476	2.843	
	2.00	0.000	230.000	230.000	750.000	0.200		1.538	0.000	
		0.000	315.000	315.000	750.000	0.800	272.500	1.538	4.190	
	3.00	0.000	185.000	185.000	690.000	0.200		1.415	0.000	
		0.000	206.000	206.000	690.000	0.800	195.500	1.415	2.765	**9.798**
12:27	1.00	15.000	150.000	150.748	900.000	0.200		1.845	0.000	
		10.000	185.000	185.270	900.000	0.800	168.009	1.845	3.100	
	2.00	12.000	200.000	200.360	990.000	0.200		2.030	0.000	
		15.000	215.000	215.523	990.000	0.800	207.941	2.030	4.220	
	3.00	0 000	185.000	185.000	960.000	0.200		1 968	0.000	
		0.000	195.000	195.000	960.000	0.800	190.000	1.968	3.739	**11.059**
13:15	1.00	0.000	55.000	55.000	1090.000	0.200		2.235	0.000	
		0.000	65.000	65.000	1090.000	0.800	60.000	2.235	1.341	
	2.00	0.000	85.000	85.000	1170.000	0.200		2.399	0.000	
		0.000	85.000	85.000	1170.000	0.800	85.000	2.399	2.039	
	3.00	0.000	60.000	60.000	1170.000	0.200		2.399	0.000	
		5.000	70.000	70.178	1170 000	0.800	65.089	2.399	1.561	**4.941**
16:10	1.00	10.000	100.000	100.499	840.000	0.200		1.722	0.000	
		0.000	120.000	120.000	840.000	0.800	110.249	1.722	1.898	
	2.00	8.000	100.000	100.319	840 000	0.200		1.722	0.000	
		16.000	110.000	111.158	840.000	0.800	105.739	1.722	1.821	
	3.00	20.000	120.000	121.655	780.000	0.200		1.599	0.000	
		15.000	125.000	125.897	780.000	0.800	123.776	1.599	1.979	**6.698**
16:15	1.00	20.000	107.000	108.853	700.000	0.200		1.435	0.000	
		12.000	110.000	110.653	700.000	0.800	109.753	1.435	1.575	
	2.00	-5.000	102.000	102.122	750.000	0.200		1.538	0.000	
		15.000	109.000	110.027	750.000	0.800	106.075	1.538	1.631	
	3.00	12.000	110.000	110.653	680.000	0.200		1.394	0.000	
		16.000	119.000	120.071	680.000	0 800	115.362	1.394	1.608	**4.814**
17:16	1.00	8.000	97.000	97.329	600.000	0.600	97.329	1.230	1.197	
	2.00	12.000	90.000	90.796	630.000	0.600	90.796	1.292	1.173	
	3.00	13.000	98.000	98.858	560.000	0.600	98.858	1.148	1.135	**3.505**
18:15	1 00	3.000	88.000	88.051	510.000	0.600	88.051	1.046	0.921	
	2.00	11.000	81.000	81.744	540.000	0.600	81.744	1.107	0.905	
	3.00	12.000	88.000	88.814	450.000	0.600	88.814	0.923	0.819	**2.645**

The sections listed in the table above are the western, middle and eastern section under the main culvert shown in figure 6, The right hand column shows the sum of the Flow in m^3 of all three sections for each time of measurement.

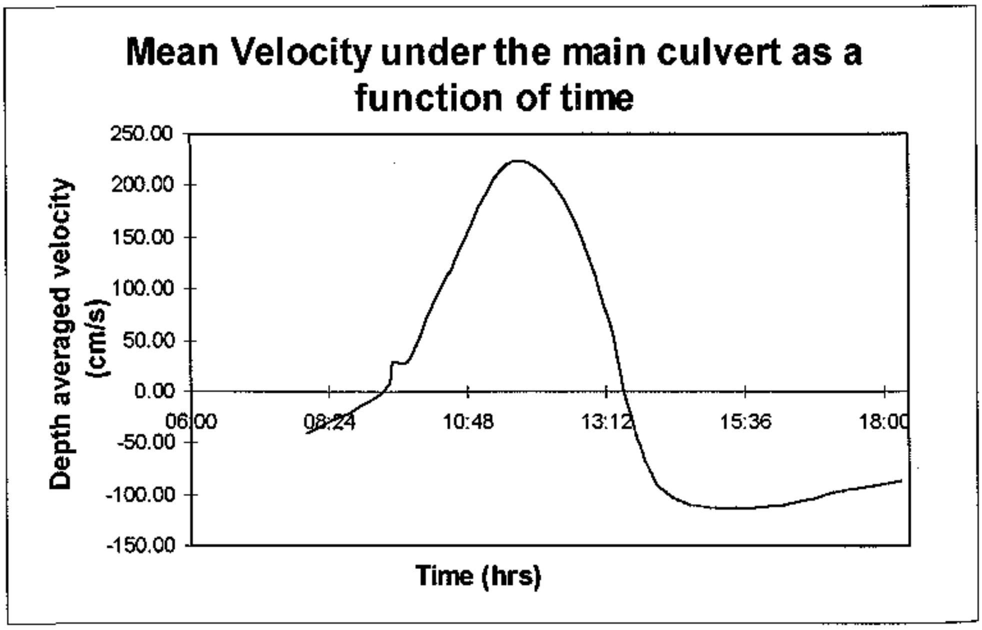
Volume Check

Input=Output

Time	Magnitude	Time	Time Weighted	M^3
05:00				
06:00	-2.5215	0.020833	-0.05253125	-94.549
07:00	-1.93725	0.041667	-0.08071875	-290.56
08:00	-0.895	0.048611	-0.043526825	-182.8
09:20	0.000	0.03125	0	0
09:30	0.610	0.008681	0.005292156	3.9688
09:45	0.608	0.014583	0.008861125	11.1641
10:12	2.475	0.017361	0.042964583	64.4417
10:35	4.677	0.026736	0.125046797	288.835
11:29	9.798	0.038889	0.381040289	1280.19
12:27	11.059	0.036806	0.407037555	1294.28
13:15	4.941	0.021875	0.10807538	204.246
13:30	0.000	0.015625	0	0
14:00	-5.6	0.020833	-0.116666667	-209.98
14:30	-6.3	0.024306	-0.153125	-321.54
15:10	-5.698	0.036458	-0.207757451	-654.38
16:15	-4.814	0.04375	-0.210612367	-796.05
17:16	-3.505	0.041667	-0.146028448	-525.66
18:15	-2.645	0.02066	-0.054640585	-97.526
19:15		Sum	0.012710541	-25.927

The Table above shows calculation of the input-output balance, the value of the sum may not equal zero but this can be attributed to the many errors which have entered the analysis through measurement and averaging.

<u>Shown Below is Flow as a function of time</u>

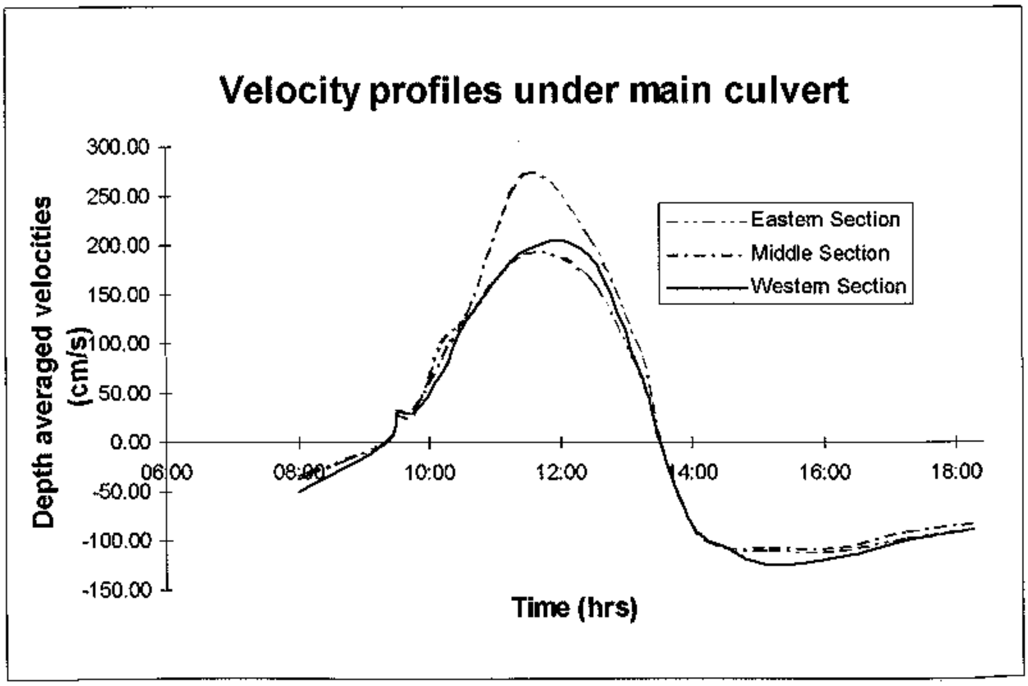


Velocity Profiles

Eastern Section		Middle Section		Western Section	
Time	Velocity Cm/s	Time	Velocity Cm/s	Time	Velocity Cm/s
08:00	-33.27	08:00	-37.38	08:00	-50.00
09:20	0.00	09:20	0.00	09:20	0.00
09:30	27.00	09:30	32.14	09:30	30.15
09:45	27.00	09:45	32.00	09:45	30.00
10:12	100.00	10:12	85.00	10:12	71.00
10:35	125.00	10:35	130.00	10:35	125.00
11:29	192.62	11:29	272.50	11:29	195.50
12:27	168.01	12:27	207.94	12:27	190.00
13:15	60.00	13:15	85.00	13:15	65.09
13:30	0.00	13:30	0.00	13:30	0.00
14:00	-84.00	14:00	-84.00	14:00	-84.00
14:30	-106.70	14:30	-106.70	14:30	-106.70
15:10	-110.25	15:10	-105.74	15:10	-123.78
16:15	-109.75	16:15	-106.07	16:15	-115.36
17:16	-97.33	17:16	-90.80	17:16	-98.86
18:15	-88.05	18:15	-81.74	18:15	-88.81

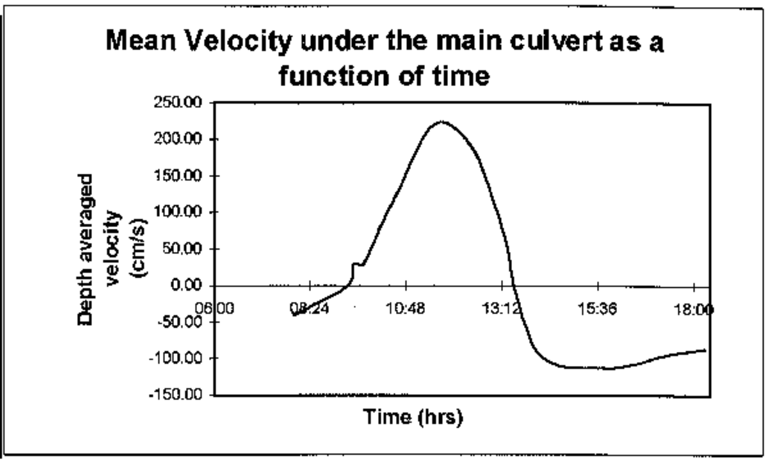
The Table of Velocities above show variation for each section

The Graph Below shows these Variations as a function of time



Mean values

Time	Avg. Vel. Cm/s
08:00	-40.21
09:20	0.00
09:30	29.76
09:45	29.67
10:12	85.33
10:35	126.67
11:29	220.21
12:27	188.65
13:15	70.03
13:30	0.00
14:00	-84.00
14:30	-106.70
15:10	-113.25
16:15	-110.40
17:16	-95.66
18:15	-86.20

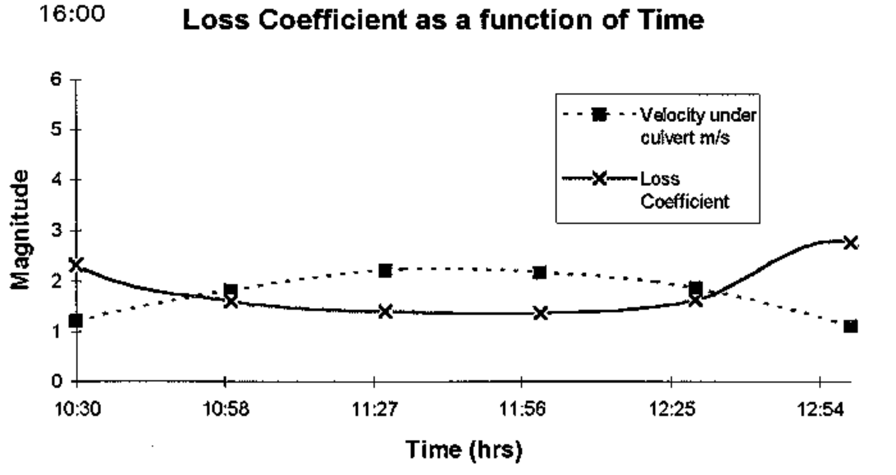


The table and graph above show the average of the velocities of all three sections under the culvert as mentioned previously

Evaluation of the Loss Coefficient

Time	Abs	hb-he	Uc	hb-he	Uc	Cl
Hours	mm	mm	Cm/s	m	m/s	
08:00	547	-547	40	-0.547	0.4	-67.0759
08:30	298	-298	26	-0.298	0.26	-86.4905
09:00	125	-125	13	-0.125	0.13	-145.118
09:30	10	10	0	0.01	0	#DIV/0!
10:00	90	90	60	0.09	0.6	4.905
10:30	170	170	120	0.17	1.2	2.31625
11:00	265	265	180	0.265	1.8	1.604722
11:30	343	343	220	0.343	2.2	1.390426
12:00	320	320	215	0.32	2.15	1.358226
12:30	283	283	185	0.283	1.85	1.62234
13:00	170	170	110	0.17	1.1	2.756529
13:30	0	0	0	0	0	0
14:00	60	-60	85	-0.06	0.85	-1.62934
14:30	130	-130	106	-0.13	1.06	-2.27002
15:00	200	-200	151	-0.2	1.51	-1.72098
					avg	#DIV/0!

16:00

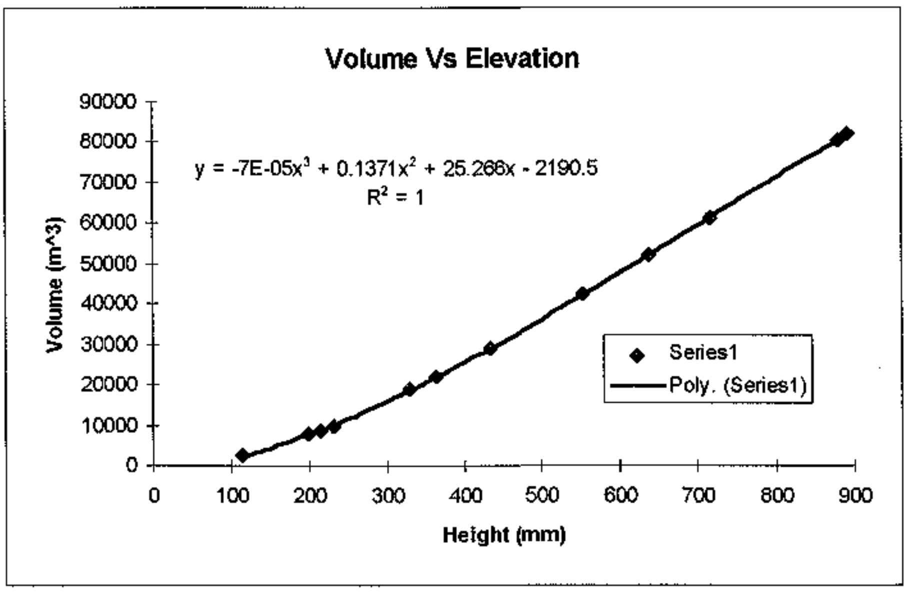


Stage	difference	Stage	Photo order	Area 1	Area 2	otal Are
892		23	8	86882	32000	118882
880	0.012	35	9	85182	31900	117082
715	0.165	200	10	84562	31900	116462
638	0.077	277	7	85362	31900	117262
553	0.085	362	11	82762	31900	114662
433	0.12	482	12	72822	31800	104622
364	0.069	551	6	70662	31900	102562
330	0.034	585	13	68042	31738	99780
232	0.098	683	1	48562	31118	79680
215	0.017	700	5	26602	30758	57360
198	0.017	717	2	35702	30168	65870
115	0.083	800	3	25842	29058	54900
61	0.054	854	4	19002	24378	43380

Data taken from Photo using Planimeter with elevation

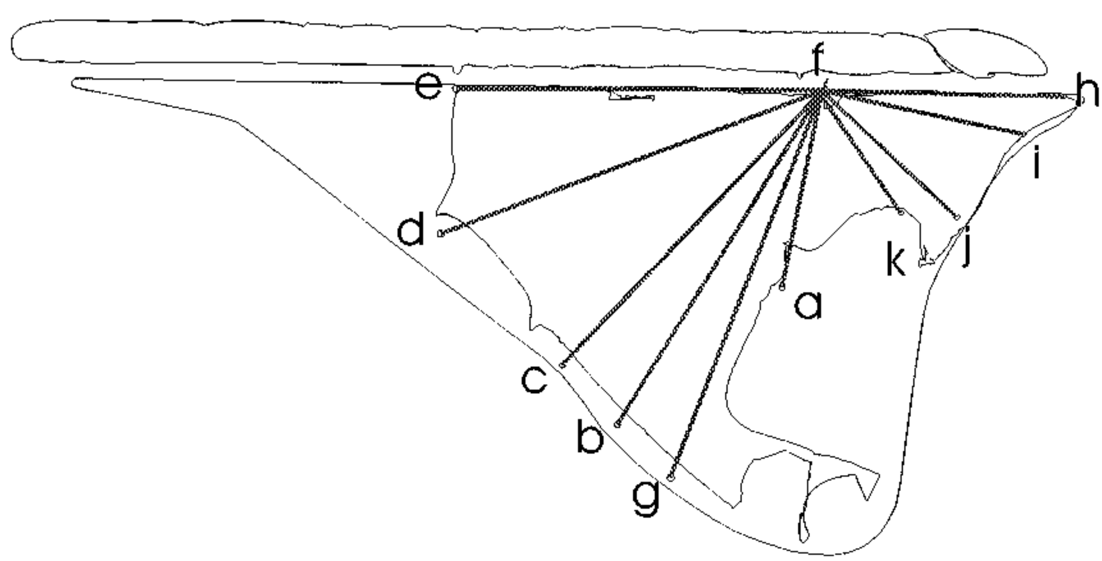
Stage m	Elevation m	Differenc m	Area m^2	chg. Vol. m^3	cum. Vol. m^3
0.892	1.092	0.012	118882	1437.384	103201.4
0.88	1.08	0.165	117082	19369.68	101764.1
0.715	0.915	0.077	116462	8936.774	82394.38
0.638	0.838	0.085	117262	10077.77	73457.61
0.553	0.753	0.12	114662	14361.84	63379.84
0.433	0.633	0.069	104622	7289.988	49018
0.364	0.564	0.034	102562	3534.402	41728.01
0.33	0.53	0.098	99780	10763.34	38193.61
0.232	0.432	0.034	79680	2943.89	27430.27
0.198	0.398	0.083	65870	5922.465	24486.38
0.115	0.315	0.054	54900	3275.64	18563.91
0.061	0.261	0.061	43380	2688.27	15288.27
0	0.2	**0.2**	**42000**	**12600**	**12600**
-0.2	0	0	0	0	0
% Volume in bay at 0 stage				12.21	

The Volume Calculation above shows the percentage volume left in the bay, the diagram below shows the Volume stage relationship with a polynomial fit.

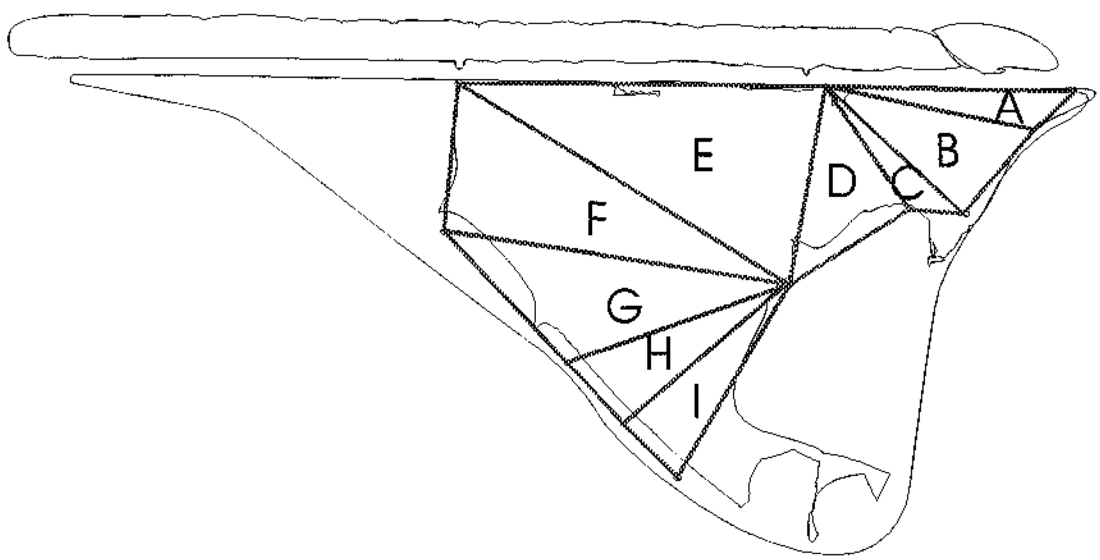


Appendix B

This section contains the data collected and used for formation of the empirical equation (equation 15) for the relationship between water level in the bay and water surface area. The benchmark used in this survey was in fact created from a grill covering a storm water sump located next to the culvert. The Bearings and distance components are not based on grid north, for this experiment this was not necessary. The only essential elements were the distances and angles.



Point	Bearing	Corr. Dist (m)	X	Y	Remarks
a	280°20'20"	190.4	34.2	-187.3	Sign in park, south of culvert
b	297°39'20"	382.9	176	-340	Southern most park bench
c	308°09'20"	365.4	227	-286	Next park bench
d	337°09'20"	381.5	352	-148	Covered info. booth
e	0°50'50"	351.4	351.3	5.204	Bay side of western culvert
g	288°55'33"	216.9	131	-381	Southern most sign (west side)
h	182°00'40"	269.7	-269.5	-9.4	Bay side eastern culvert
i	196°48'18"	209.6	-200.7	-60.6	Telephone pole on bend
j	231°24'39"	207.2	-129.2	-162.0	Tree east side of small bay
k	240°17'35"	196.5	-97.371	-170.7	last Shrub around edge of bay



The diagram above shows the areas formed from the survey grid and used in establishing the bay surface area relationship

Surveyed triangles	Area m^2
A	7,217
B	11,957
C	3,149
D	12,035
E	32,986
F	23,413
G	19,477
H	7,728
I	6,356

The following pages show, Firstly the sequence of time lapse photos of the main bay **pages 48, 49 &50** and then six additional photos of the eastern bay **page 51**. Following these are the surface areas measured on the grid formed for the main bay pages **52&53** and the eastern bay pages **54&55**.

1

6:10am

2

7:00am

3

8:00am

4

9:00am

5

10:06am

6

11:12am

7

12:15pm

8

1:08pm

9

2:09pm

10

3:04pm

11

4:04pm

12

5:07pm

13

6:04pm

1

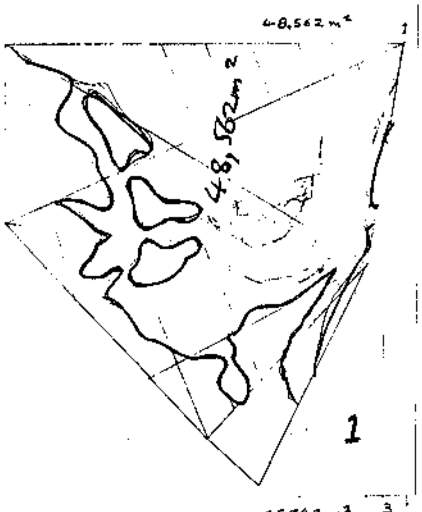
2

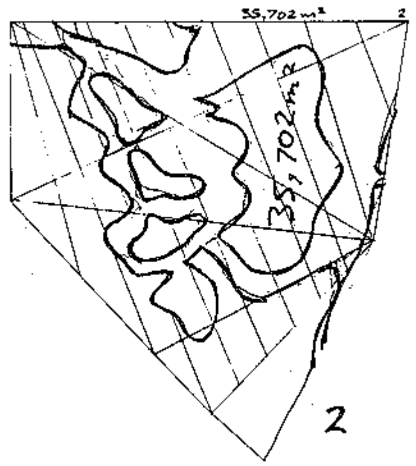
3

4

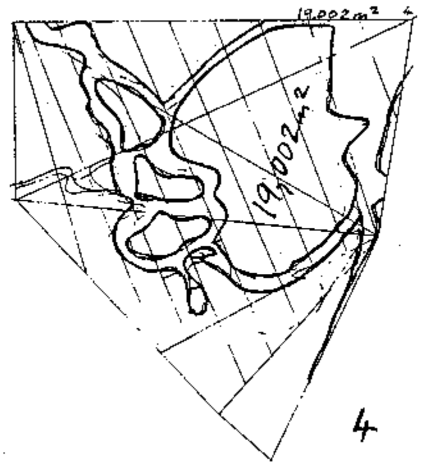
5

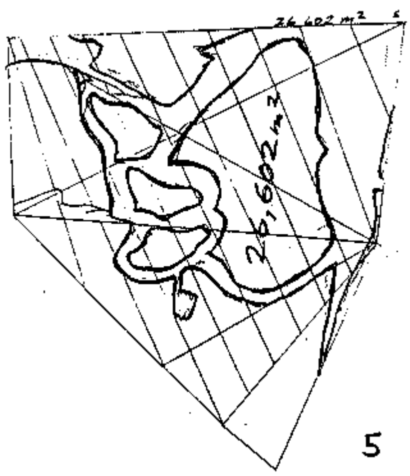
6

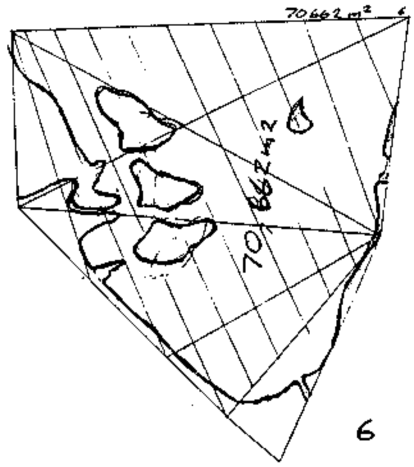

48,562 m^2 1
48,562 m^2
1

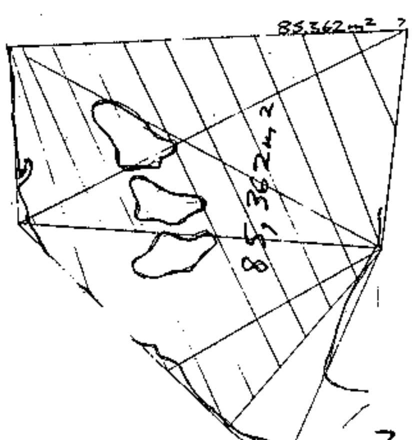

35,702 m^2 2
35,702 m^2
2

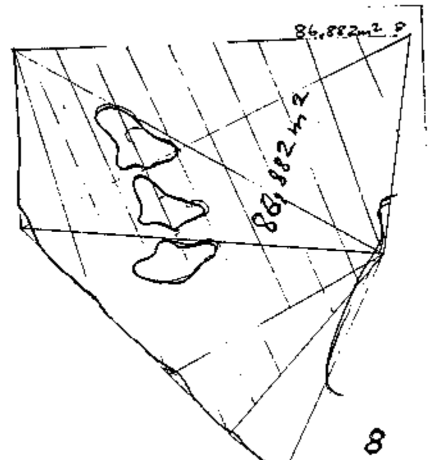

25,842 m^2 3
25,842 m^2
3

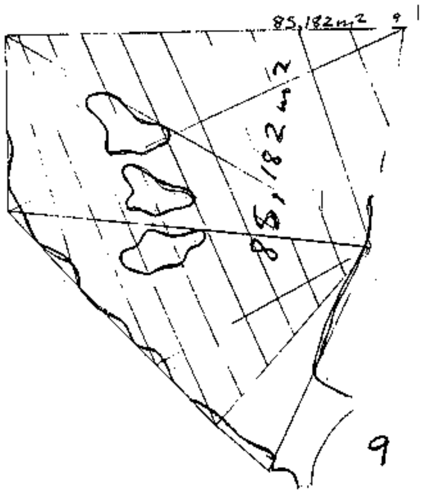

19,002 m^2 4
19,002 m^2
4


26,602 m^2 5
26,602 m^2
5

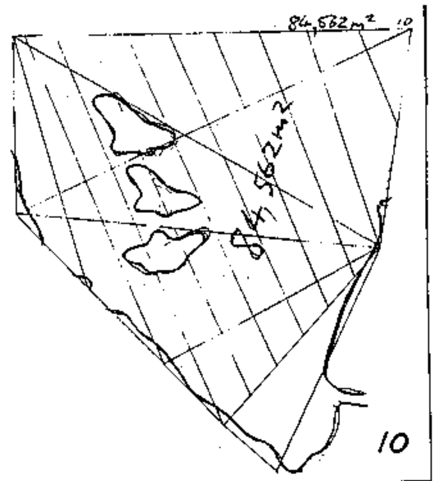

70,662 m^2 6
70,662 m^2
6


85,362 m^2 7
85,362 m^2
7

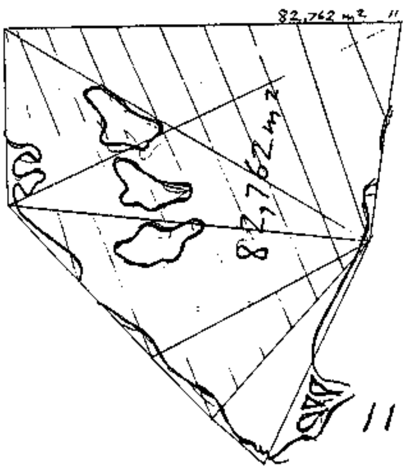

86,882 m^2 8
86,882 m^2
8


85,182m²
9
85,182 m²

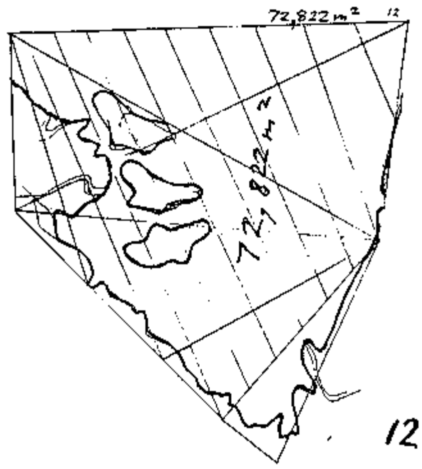
9


84,562m²
10
84,562m²

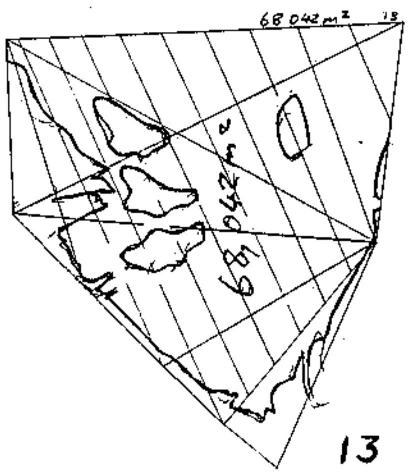
10


82,762 m²
11
82,762m²

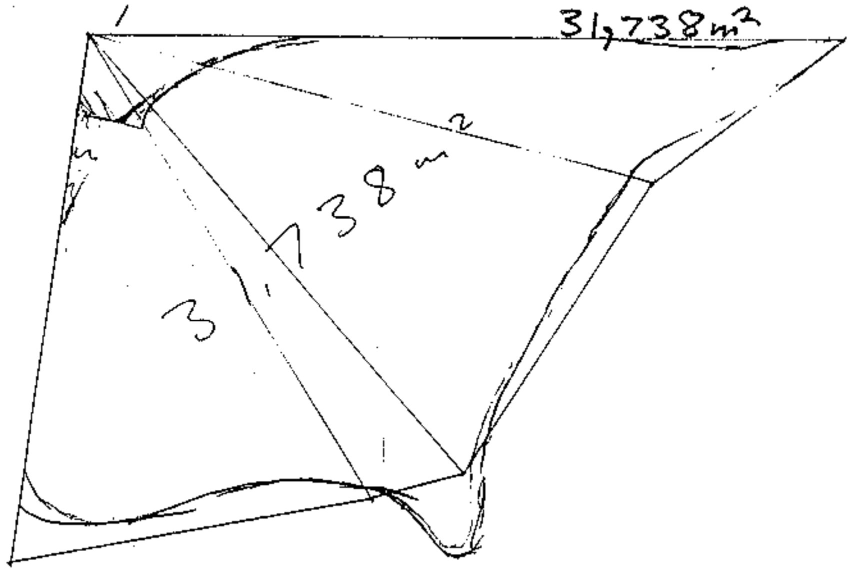
11

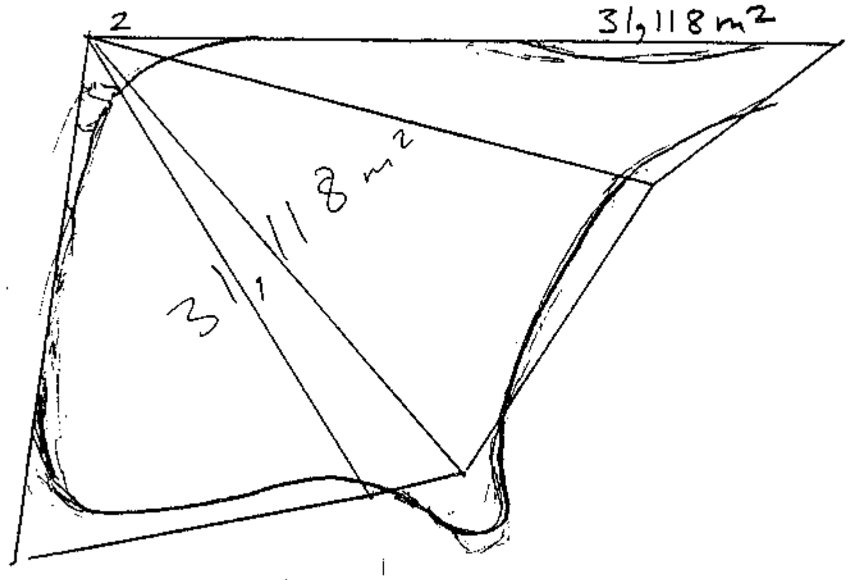

72,822m²
12
72,822m²

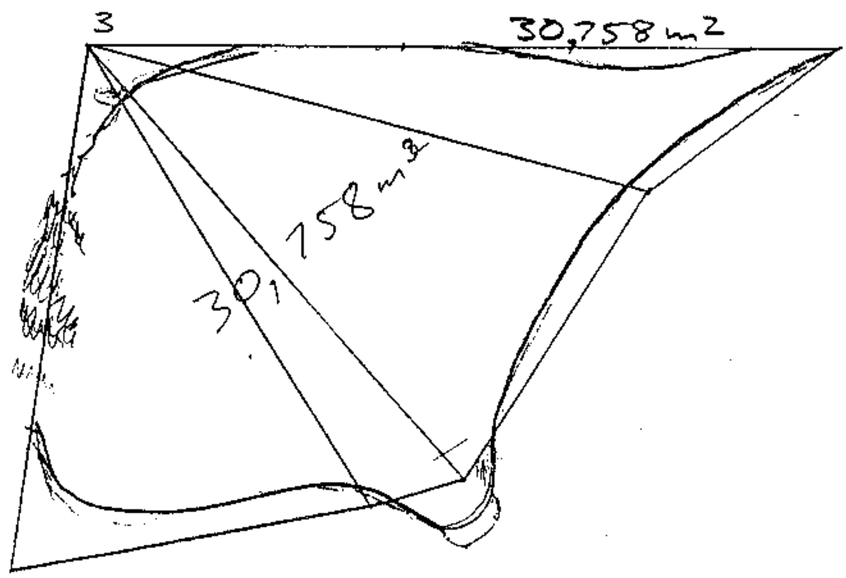
12

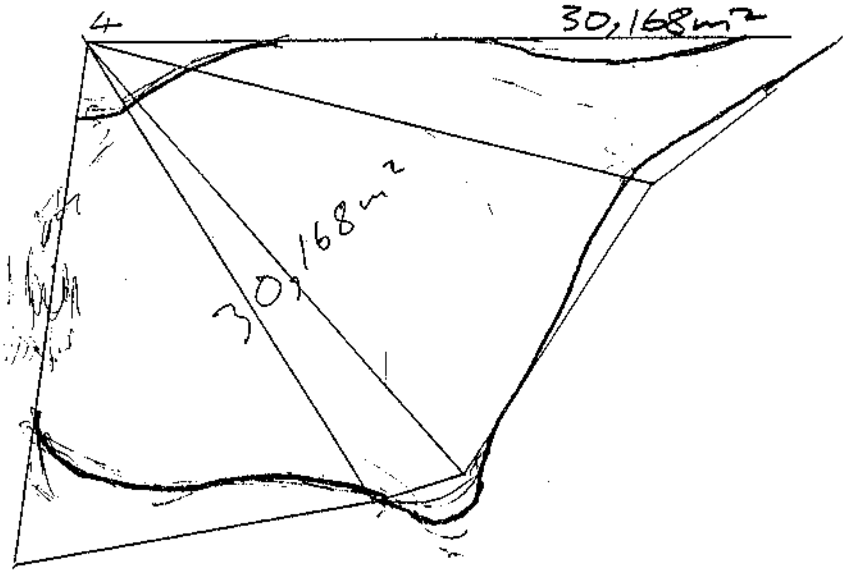

68 042m²
13
68,042m²

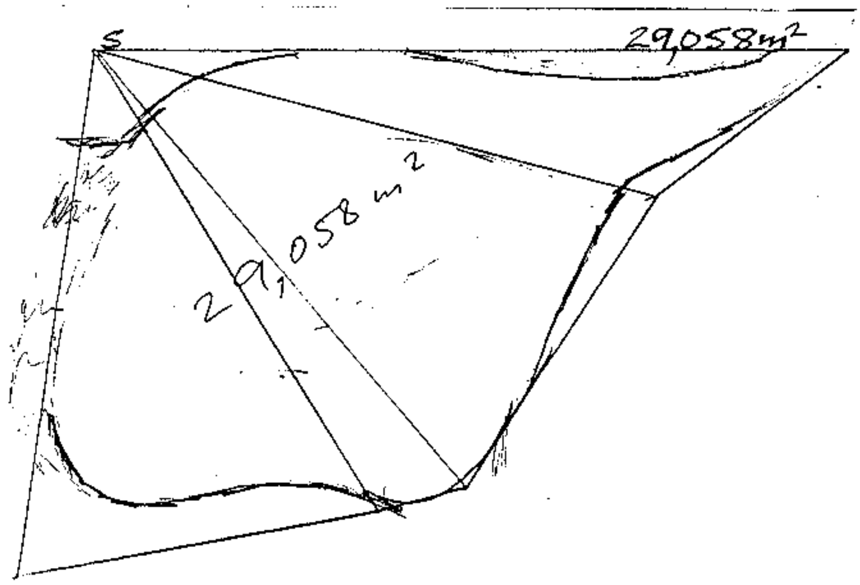
13

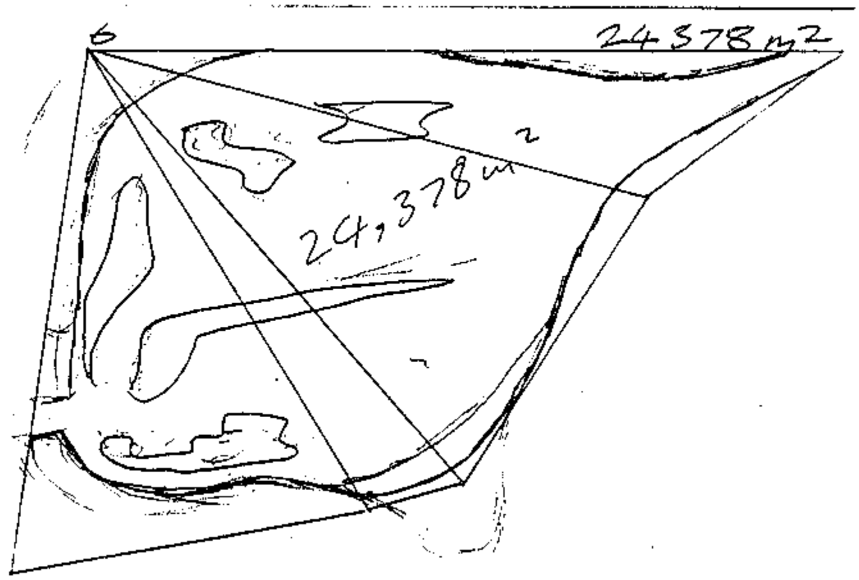

1
31,738 m²
31,738 m²


2
31,118 m²
31,118 m²


3
30,758 m²
30,758 m²

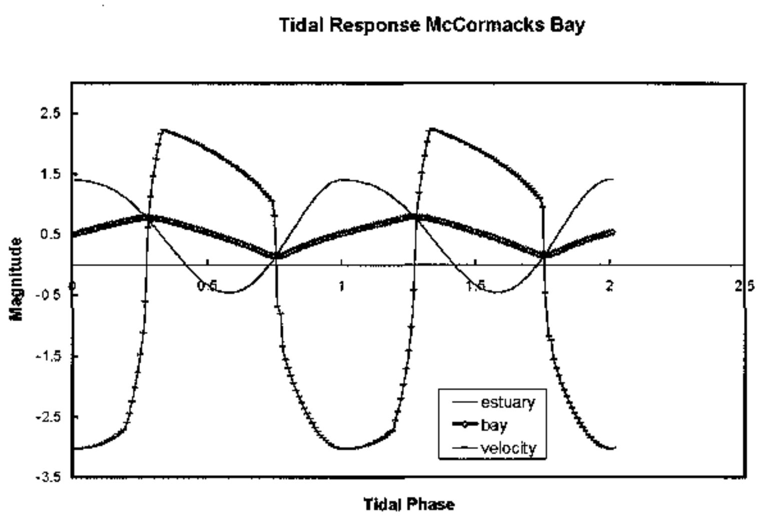

4
30,168m²
30,168m²


5
29,058m²
29,058m²

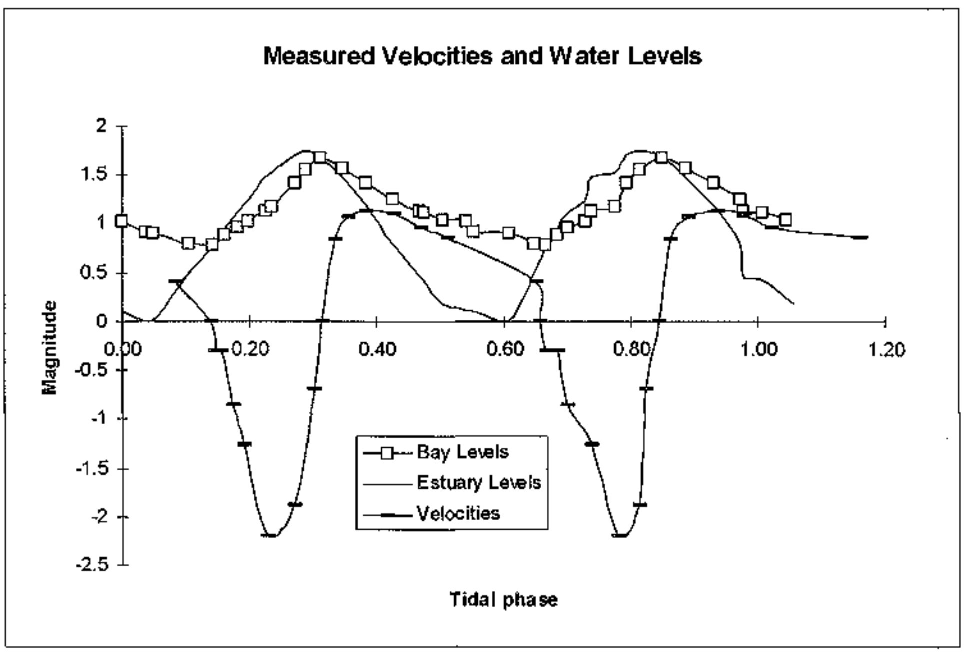

6
24,378m²
24,378m²

Appendix C

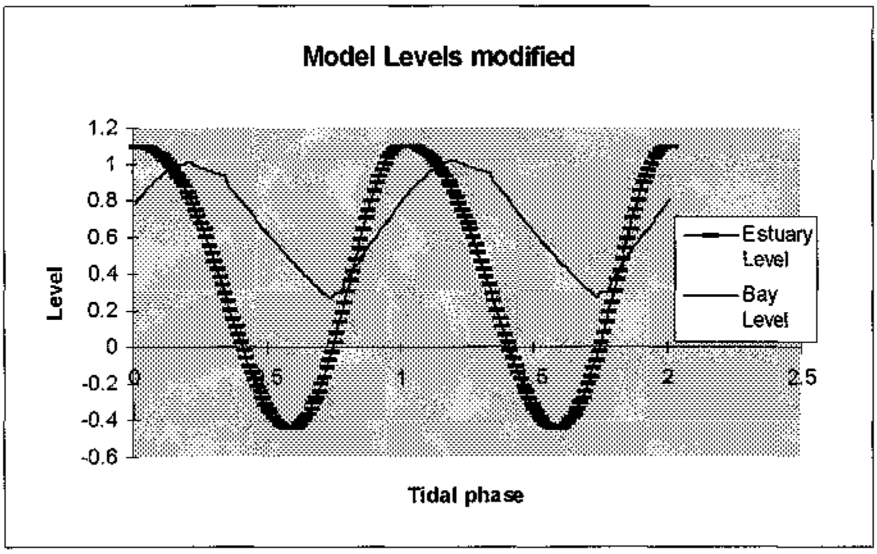
The outputs from the model are compared below with those measured in the estuary. Both plots show the same characteristics flow occurring coincidently. The main differences between the two being the magnitude and shape.



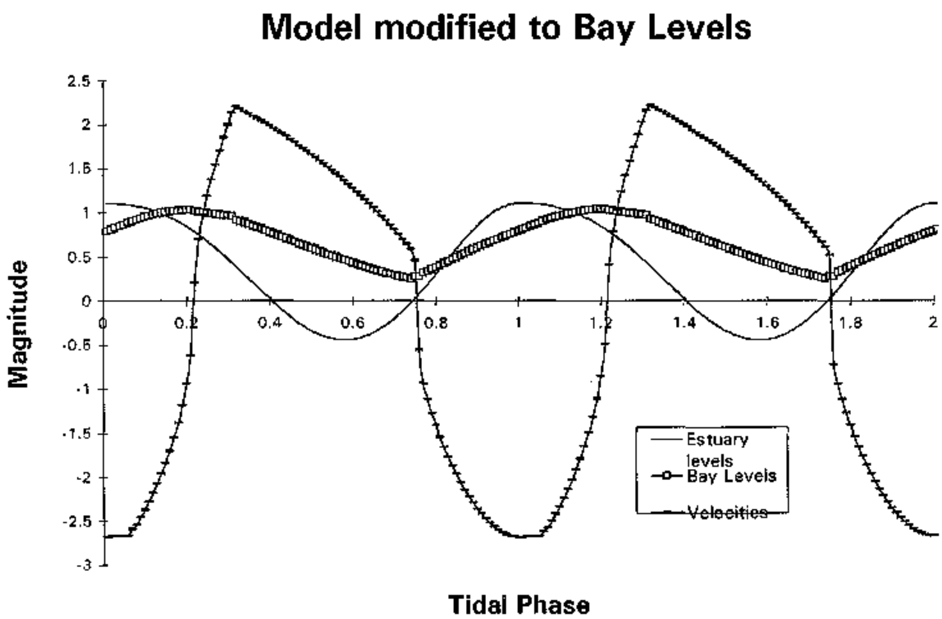
The model output shown in the chart above differs, from the chart below of observed characteristics, primarily in the shapes of the curves. The generated curves of the model are very symmetric and cyclic whereas the curves of the measured characteristics below show unevenness and asymmetry. The magnitudes of the levels and velocities as well as cross-over points differ between the two and well as differences in level maxima and minima.



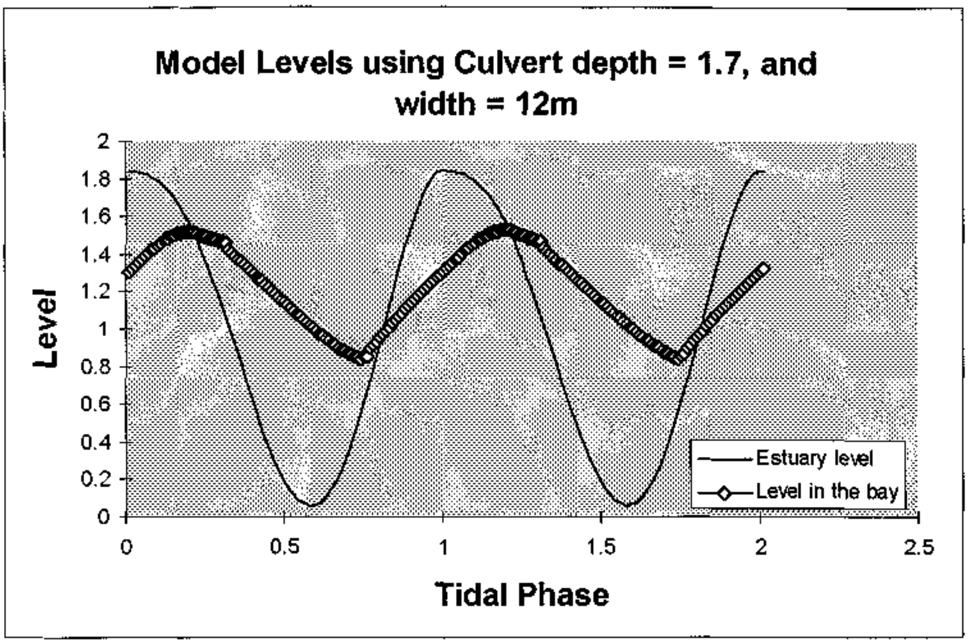
By modifying the existing model output to a form closer to that of the measured characteristics a chart like that below was produced.

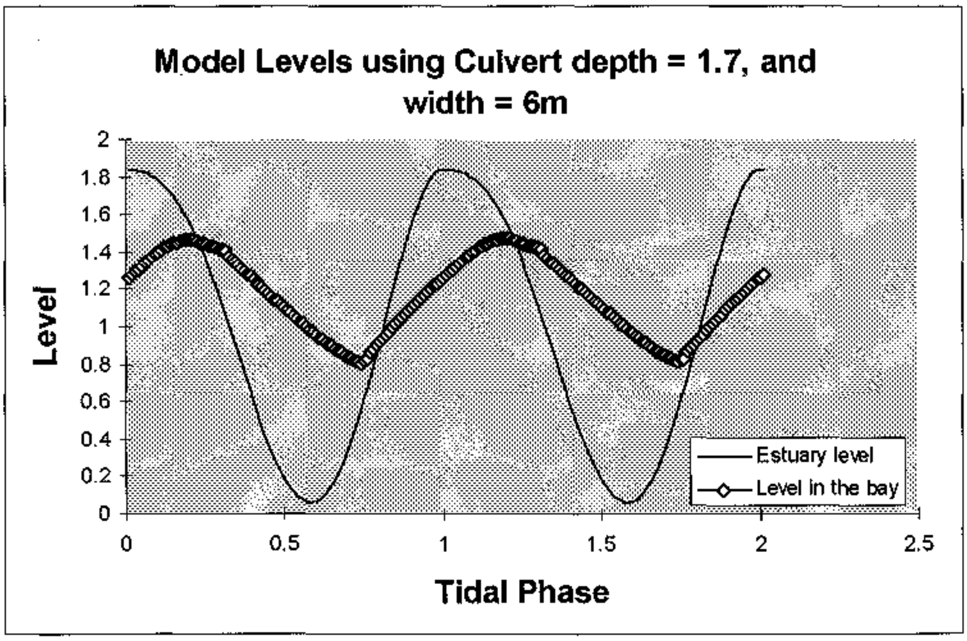


The magnitudes and differences at maxima and minima are very similar to those of the measured values. The modified model out put can be now used to accurately predict the change in bay levels.



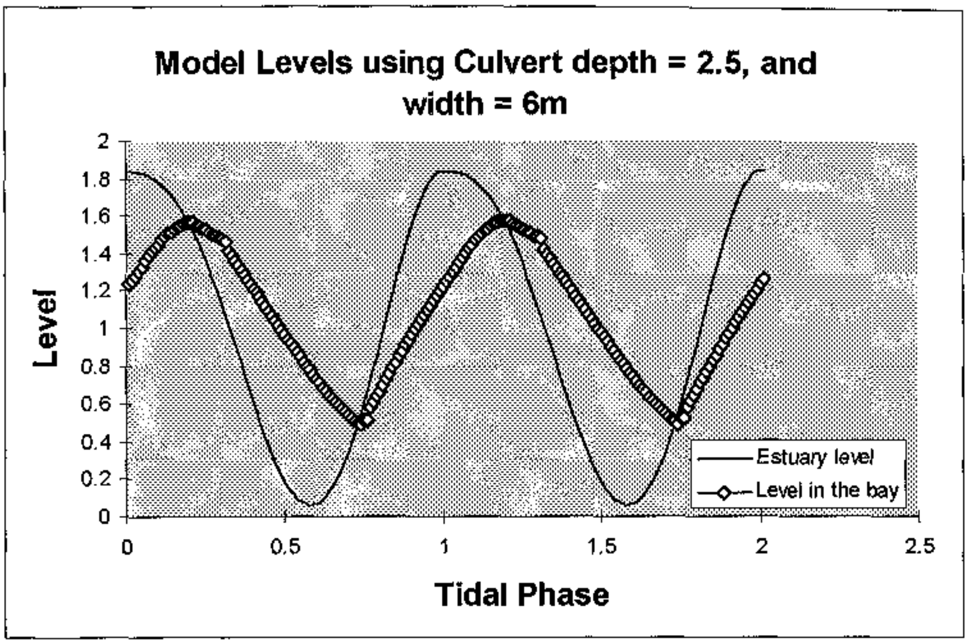
To gain a greater understanding of how changing the characteristics of the culvert geometry and particularly the invert level. Four different dimensions were trialed to show possible increases in the bay level. Changes in the range of bay water levels effect the amount of water entering and exiting the bay.



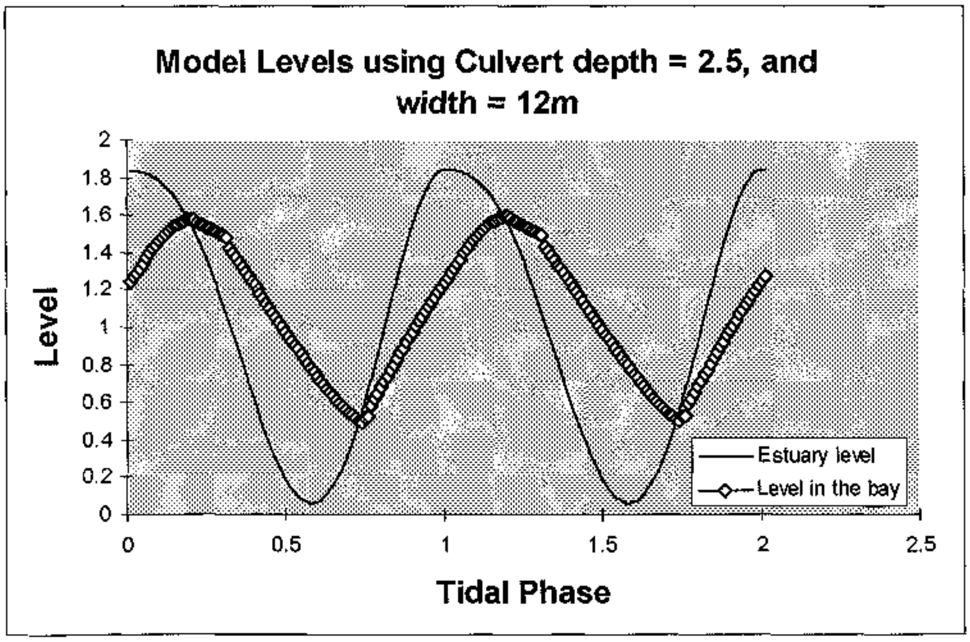


In the above charts it can be seen that increasing the culvert width has no dramatic effect on the range of bay levels. The culvert width was doubled to 12m, and the range of levels in the bay changed by 0.01m.

By increasing the height of the culvert to 2.5m, and in so doing dropping the invert level by 0.8m the effects were of a greater magnitude. This follows logically as the culvert is less of vertical constriction to the flow and reduces the pooling of water in front of the culvert.



It can be seen from the chart above that by increasing the height of the culvert, the bay's water level range increased by 0.2m that is an increase in range of 23% compared with a height of 1.7m.



By comparison it can be seen from the chart above increasing the width at a height of 2.5m increases the water level range in the bay by 0.21 over a 6m wide and 1.7m high culvert.